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By G. Murphy

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TWO-PHASE IMPURE STEAM FLOW

ABSTRACT A device has been developed to remove the prominent impurity carbon dioxide gas from steam. The technique consists of a heat exchanger that condenses some of the impure steam to produce a pure condensate. The condensate is fed back to the shell side of the heat exchanger for conversion to pure steam while cooling the impure steam on the tube side. This regenerator, called the Inverse Flash Steam Purifier, is a small, self contained system with no moving parts nor electrical power requirements.

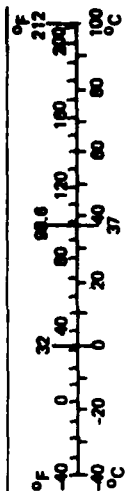
The Inverse Flash Steam Purifier concept was tested in the laboratory and found to have very promising performance characteristics. Carbon dioxide levels were reduced from over 100 ppm to less than 3. This allows consideration of using the concept to purify shore-to-ship steam.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures				Approximate Conversions from Metric Measures			
Symbol	When You Know	Multiply by	To Find	Symbol	When You Know	Multiply by	To Find
LENGTH				LENGTH			
in	inches	2.5	centimeters	mm	millimeters	0.04	inches
ft	feet	30	centimeters	cm	centimeters	0.4	inches
yd	yards	0.9	meters	m	meters	3.3	feet
mi	miles	1.6	kilometers	km	kilometers	1.1	yards
AREA				AREA			
in ²	square inches	6.5	square centimeters	cm ²	square centimeters	0.16	square inches
ft ²	square feet	0.09	square meters	m ²	square meters	1.2	square yards
yd ²	square yards	0.8	square meters	km ²	square kilometers	0.4	square miles
mi ²	square miles	2.6	square kilometers	ha	hectares (10,000 m ²)	2.5	acres
MASS (weight)				MASS (weight)			
oz	ounces	28	grams	g	grams	0.036	ounces
lb	pounds (16 ounces)	0.45	kilograms	kg	kilograms	2.2	pounds
	short tons (2,000 lb)	0.9	tonnes	t	tonnes (1,000 kg)	1.1	short tons
VOLUME				VOLUME			
tsp	teaspoons	5	milliliters	ml	milliliters	0.03	fluid ounces
Tbsp	tablespoons	15	milliliters	l	liters	2.1	pints
fl oz	fluid ounces	30	milliliters	ml	liters	1.06	quarts
c	cups	0.24	liters	l	liters	0.26	gallons
p	pints	0.47	liters	m ³	cubic meters	36	cubic feet
qt	quarts	0.95	liters	m ³	cubic meters	1.3	cubic yards
gal	gallons	3.8	liters	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature
ft ³	cubic feet	0.03	cubic meters				
yd ³	cubic yards	0.76	cubic meters				
TEMPERATURE (exact)				TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature

* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10.286.



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INTRODUCTION

This effort identifies a concept for improving the purity of steam. It focuses on steam-side treatment rather than feedwater side. Feedwater treatment, such as demineralization and reverse osmosis (RO), is currently utilized by the Navy and industry to produce clean steam. The shore Navy, however, has a special problem. Its shore boilers produce steam for base facilities as well as for berthed ships. In the past, water softeners were adequate for producing the low pressure (<300 psig) shore steam. The Naval Sea Systems Command (NAVSEA) later introduced a new requirement for using the shore steam (Table 1 and Ref 1), as a hot lay-up for the ship boilers. This so-called "boiler blanketing" has the advantages of reducing ship engineering labor while in port, lengthening equipment life, and providing an improvement in ship underway readiness--a hot boiler means a rapid lightoff.

On the average, 50 percent of the steam produced by shore boilers, goes to the ships berthed in port. Less than 10 percent of the shore steam arriving at the ship is used for boiler blanketing. The remainder is for galley, scullery, space heating, hot water, and laundry services. This suggests that approximately 5 percent of the shore steam is produced solely for ship boiler blanketing. The amount of steam required by the Fleet also varies with the number of ships berthed, which can range from typically 30 percent of the total home-ported ships to more than 75 percent near holidays.

The demineralization and RO treatment of shore boilers purifies 100 percent of the total exported steam. However, only ship boilers require this higher purity level of steam. In other words, 95 percent of the steam generated does not require this additional improvement in purity. It was for this reason and for the potentially enormous cost savings involved that steam-side treatment was being examined.

The work effort is part of the Inhouse Independent Laboratory Research Program funded by the Office of the Chief of Naval Research.

BACKGROUND

There are 32 home ports that provide utility services to the Fleet. For steam alone more than 35 million million (10^{12}) BTUs of energy are demanded annually by the ships in port. Few Navy activities have dedicated shore boiler plants for ship use. Most activities have more than one boiler plant, each with more than one boiler, that provide steam to both the base and the ships. The boilers are generally package water tube boilers that provide steam at less than 450 psig and flow rates ranging from 10,000 to 150,000 lbm/hr. In the past, boiler makeup water was treated using sodium zeolite ion exchangers. These replaced calcium

and magnesium ions with less harmful sodium ions. Typically, sodium sulfites, phosphates, and tannins were added to further condition the feed/boiler water.

Steam leaving the boilers generally had a pH level near 4, a conductivity varying from 12 to 30 $\mu\text{mho/cm}$, a silica level sometimes greater than 0.2 ppm (parts per million), and a hardness sometimes greater than 0.1 epm (equivalent to per million). The pH and conductivity often did not satisfy the new NSTM standards (Table 1). When neutralizing amines were added to increase the pH, the conductivity would rise above 25 $\mu\text{mho/cm}$. The dissolved silica and hardness contaminant levels in the steam, however, could be removed.

Steam Separators

The highly transient steam demands of home-ported ships (Ref 2) during an average day often caused impurities (e.g., silica) to flow from the boiler into the steam line. The simple flat plate baffle inside the boiler drum was inadequate to prevent this carryover. Subsequently, steam separators were examined (Ref 3) for their ability to remove contaminants that entered the boiler export line. Some were found to have astonishing qualities in removing heavy contamination in poor quality steam. However, they were unable to remove any noncondensable gases. While dissolved solids could be removed, the gases remained.

Water Treatment

The low pH in the steam was found to be caused by carbon dioxide (CO_2). Carbon dioxide and water generate carbonic acid, which is responsible for the acidic pH readings in a steam sample. Carbon dioxide comes about from bicarbonates in the feedwater. The bicarbonates are not removed by water softeners, but they can be by demineralizers and reverse osmosis (RO) water treatment systems. These systems have been and are being installed at all Navy home ports where there is a clean steam requirement.

The steam produced by the feedwater system satisfies the NSTM standards (Table 1). Steam exported from these shore boilers has a conductivity near 2 $\mu\text{mho/cm}$ and a pH near 7. Even though neutralizing amines must still be introduced to increase the pH to 8-9.5, the conductivity will remain within specifications ($<25 \mu\text{mho/cm}$).

While water treatment is a proven method for producing clean steam, it unnecessarily purifies 100 percent of the total exported steam. The need for only 5 percent of the steam to be purified offers the incentive to research steam-side treatment alternatives.

Steam-Side Characteristics

The steam environment in shore distribution systems is severe (high temperatures, pressures, and velocities) and complex (two phases, turbulent, and nonlinear). Attempting to sample the steam in this environment has led to a more thorough understanding of flow/contaminant interactions. The need to exercise and develop critical sampling techniques, and subsequent testing, has given insight to some promising steam-side treatment concepts.

To measure the impurity levels in steam, it is necessary to withdraw a portion of steam from the steam main through stainless steel tubing, condense the steam with a heat exchanger, and then analyze the now liquid sample through analytical chemistry (grab sample) or monitoring instruments (site analysis).

The levels of contaminants strongly depend upon where and how the sample is withdrawn. As steam loads in shore distribution systems can vary widely at the end use points, (e.g., a factor of 5 in 30 seconds), a means was developed (Ref 4-6) for sampling the steam isokinetically and automatically (Figure 1). Isokinetic sampling is withdrawing the steam sample such that the port velocity (Figure 1a) is identical to the steam main velocity. This is required in two-phase flow, which exists in the Navy's saturated steam distribution systems.

The Automated Steam Purity Measurement System (SPMS) shown in Figure 1 makes it possible to track changes in steam flow rate and pressures (Ref 7). More importantly, it is possible to determine the influence of sampling techniques upon the contaminant level measured. These include sampling with and without a probe; sampling from a port at the pipe top, bottom, and side; and sampling at less than and greater than isokinetic velocities.

When testing the automated isokinetic sampling and analysis system (Appendix A and Ref 6), a curious behavior in steam purity data was observed (Figure 2). At low steam flow rates (~500 lbm/hr), the conductivity at the pipe bottom (~2 $\mu\text{mho/cm}$) was substantially less than that at the pipe top (~20 $\mu\text{mho/cm}$). The pH level was near 7 on the bottom and 4 at the top. As the steam flow rate increased from 500 lbm/hr to 2,000, these variations converged to values independent of flow changes. Similar behavior was noted in the field (Ref 5), and it was attributed to a stratified flow condition.

The significance of this curious result is that the pH (~7) and conductivity (~2 $\mu\text{mho/cm}$) level at the pipe bottom are not only different but desirable. These levels are similar to those in steam generated from demineralization, not those from water softeners.

To clarify these early observations (Ref 6) of fluid properties at the wall boundary, testing was initiated at a different site and test network (Appendix A). The only requirements imposed were that the feed-water would be softened, the generated steam must flow through a horizontal pipe, and samples would be withdrawn isokinetically. The test results are shown in Figure 3. (Earlier observations are represented as open data points in contrast to solid data points of the current tests.) The pH levels as well as the conductivity are seen to be very similar. Note that the conductivity has been normalized, since the incoming or reference steam conductivity from the earlier and recent tests were very different (e.g., 20 $\mu\text{mho/cm}$ vs 13 $\mu\text{mho/cm}$). Yet in spite of the variation, there continues to be a near order of magnitude increase in conductivity from bottom to the top of the pipe.

To expand the impurity definition from the pipe wall, measurements were made at discrete transverse points from the bottom to the top (Figure 4). The values indicate near constant core properties (pH of 4, conductivity of 6 $\mu\text{mho/cm}$), but diverge at the pipe boundary.

The low steam flow rates and the single port probe for point sampling produced a very low sample withdrawal rate, and an extremely long time to reach steady state conditions in the sampling system. A typical measurement time was 16 hours (Appendix B), particularly when measuring a relatively pure sample (i.e., $<2 \mu\text{mho/cm}$). The long times are the results of slow sample transport and flushing of residual contaminants in the sample line.

Analysis of the impure steam samples taken from the core and upper wall showed that the contaminant was mainly carbon dioxide. Measurement using a conductivity device and titrations produced similar magnitudes. Carbon dioxide in the steam is caused by bicarbonates in the feedwater. Sodium ion exchangers do not remove them. When the bicarbonates enter the boiler, they breakdown and release carbon dioxide, that has no difficulty in entering the export steam line. Carbon dioxide does two things. It increases the steam conductivity, and it also causes a significant drop in pH. For example, a mere 10 ppm carbon dioxide in the steam produces a minimum conductivity of $5 \mu\text{mho/cm}$ and a pH of 5. Figure 5 shows the relationship of conductivity, pH, and ppm carbon dioxide under the specific conditions noted and was deduced from Reference 8. Carbon dioxide absorbed by condensate produces carbonic acid and causes the low pH.

Summary of Existing Knowledge

A review of the test data in Figures 2 through 4 leads to certain conclusions. For example, sampling at the pipe bottom, either with or without a probe, yields a very low conductivity. This is attributed to a liquid film that wets the pipe wall (two-phase annular flow), which persists in saturated steam flow of Navy steam distribution systems. The liquid film easily flows down the sample withdrawal tube, since it is in the direction of gravity. Although some gas is also withdrawn, it is proportionally less, by mass. If the liquid contains little absorbed carbon dioxide (low solubility) in spite of the high steam pressure, then the overall sample conductivity reading should be relatively low ($\sim 2 \mu\text{mho/cm}$), which it is. Conversely, sampling steam at the pipe top with an upward withdrawal makes it too difficult for the liquid film or droplets to flow up the sample tube. At low steam velocities, the sample upward withdrawal velocity is insufficient to overcome the gravitation effects on the liquid film. Since just vapor would be removed from the steam line, it would contain proportionally more carbon dioxide than for bottom sampling, and result in a higher conductivity reading ($\sim 20 \mu\text{mho/cm}$). Furthermore, as the steam main velocity increases, the sample withdrawal velocity would also increase (isokinetic sampling), eventually reaching the point of overcoming the liquid inertia in upward withdrawal; then both top and bottom readings become similar (Figure 2).

It was presumed that carbon dioxide exists as a gas in the water vapor and also as an absorbed gas in the liquid. In carbonation processes, the carbon dioxide concentration in water decreases with temperature, but increases with pressure. These data are lacking at the high pressures and temperatures experienced in Navy steam distribution systems, but they can be extracted from acquired test data (Appendix B).

The test data and conclusions suggest a favorable condition existing in high pressure, saturated, steam distribution systems. The liquid film at the wall is suspected of retarding carbon dioxide, and therefore, possesses minimal acidic properties (pH ~7) and, in this case, a corresponding low conductivity (~2 $\mu\text{mho/cm}$). This observation can be capitalized upon in the production of pure steam for ship boilers.

CARBON DIOXIDE IN STEAM

Carbon dioxide causes the low pH that plagues shore-produced steam. There are a limited number of ways of removing it. Currently, carbon dioxide in steam is prevented by using water treatment methods, such as demineralizers and RO units, that take out the responsible bicarbonates and other contaminants. On the steam side, there are no known methods for carbon dioxide removal.

The amount of carbon dioxide that exists in steam and must be removed is indicated in Figure 6 (Ref 7). The figure also suggests the amount of neutralizing amine (e.g., NH_3) that needs to be added to increase the pH to 8-9.5. The NSTM standard (Table 1) requires shore steam to have a conductivity less than 25 $\mu\text{mho/cm}$ and a pH between 8-9.5. This is represented by the shaded area in Figure 6. From this figure, it appears that steam can tolerate about 8 ppm of carbon dioxide. Adding 4 ppm of NH_3 will raise the pH to 8 and the conductivity to 25 $\mu\text{mho/cm}$.

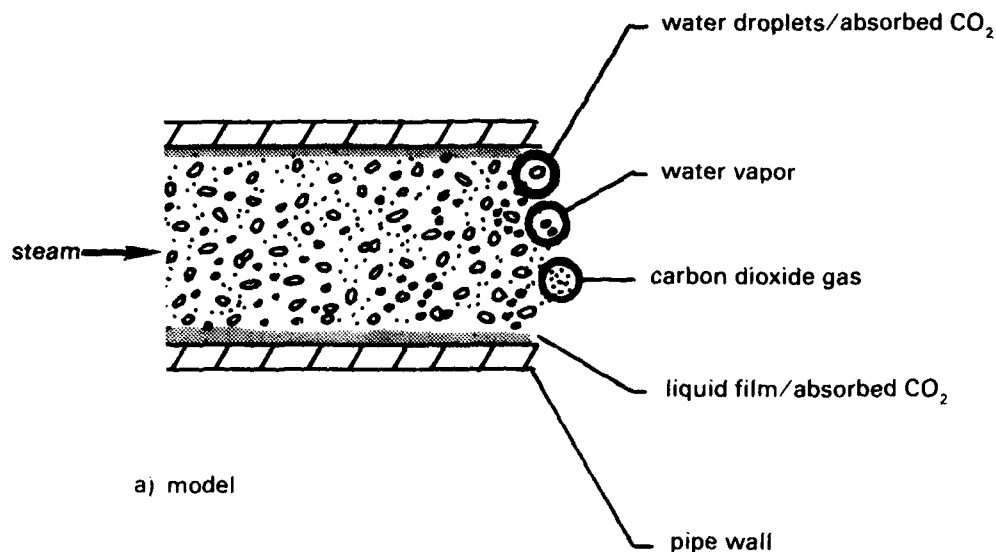
When demineralizers/RO water treatment systems produce steam (pH ~7, conductivity ~2 $\mu\text{mho/cm}$), the carbon dioxide content is near 1.0 ppm (Figure 6). Approximately 0.1 ppm NH_3 would have to be added to raise the pH from 7 to 8.

When sodium zeolite ion exchangers (water softeners) produce shore steam (pH ~4, conductivity ~20 $\mu\text{mho/cm}$), the carbon dioxide content is near 300 ppm (Figure 6). Approximately 30 ppm NH_3 would have to be added to raise the pH from 4 to 8, but the conductivity would now be at 200 $\mu\text{mho/cm}$, instead of 20.

Therefore, based on the above data, steam-side treatment (using water softeners) would have to reduce the carbon dioxide content from nearly 300 ppm to less than 8 ppm. This is the goal.

THEORETICAL MODEL

It is surmised that carbon dioxide is a component of steam that is distributed predominately as a gas in water vapor (binary gas) and lesser as an absorbed gas within the liquid (dispersed droplets and wall film). This selective distribution was deduced from laboratory testing, as previously discussed. The shore steam is actually a two-phase flow, multi-component fluid, as illustrated below:



Two-phase, multi-component flow.

Presuming a concept can be devised to separate the carbon dioxide from the steam, an estimate of the separation capabilities, α , can be acquired by evaluating vapor-liquid equilibrium; this is done by setting the fugacity:

$$f_i^V = f_i^L \quad (1)$$

For a vapor:

$$f_i^V = \phi_i X_i^V P \quad (2)$$

For the liquid:

$$f_i^L = \gamma_i X_i^L f_i^{OL} \quad (3)$$

Considering water as a condensable,

$$\gamma_i > 1 \text{ as } X_{H_2O}^L \rightarrow 1 \quad (4)$$

and carbon dioxide as a noncondensable,

$$\gamma_i^* > 1 \text{ as } X_{CO_2}^L \rightarrow 0 \quad (5)$$

Therefore, a noncondensable component (i) in a multicomponent mixture is expressed as:

$$f_i^L = \gamma_i^{*(P^r)} X_i^L H_{i,M}^{(P^r)} \exp \int_{P^r}^P \frac{\bar{v}_L}{RT} dP$$

which evolves to

$$f_i^L = X_i^L H_{i,M}^{P^r}$$

where $H_{i,M}^{P^r}$ is Henry's law constant evaluated at any reference pressure, but at system temperature. The variation relative to standard-state fugacity is roughly fitted by:

$$H_{i,j}(T_1) = H_{i,j}(T_2) \exp \left[-7.534 \left(\frac{T_{ci}}{T_1} - \frac{T_{ci}}{T_2} \right) - 2.598 \ln \left(\frac{T_1}{T_2} \right) \right] \quad (6)$$

or the inverse separation factor, δ , is

$$\delta = \frac{X_i^V}{X_i^L} = \frac{H_{i,M}^{(T_2)} \exp \{ \}}{P} \quad (7)$$

at any temperature T_1 . Assuming a system at 20 bars and a Henry's Law constant of 3400 (actually unknown, but estimated from Equation 6), then,

$$\delta = 646$$

This suggests that if a mixture of liquid, water vapor, and carbon dioxide (at 20 bars saturation) can be separated to a carbon dioxide lean and a carbon dioxide rich stream, then the rich side would have 646 times more carbon dioxide (by mass) than the lean side. For example, impure steam purified to a 1-ppm carbon dioxide stream would have a complementary concentrate stream of more than 600 ppm carbon dioxide. Over the operating conditions expected in steam distribution systems, the separation parameter, α , sustains a high value. It varies from 600 to 1,200 and appears quite attractive, if a concept for the separation process can be achieved.

LABORATORY TESTING

Experimental testing was conducted at the NCEL Steam Laboratory (Figure 7). Saturated steam is supplied by a Keystone 5.18 MMBTU/hr watertube package boiler (natural gas fired) having a 5,000-lbm/hr steam flow rate capacity at 125 psig. Makeup feedwater treated by a sodium ion exchanger flows into a holding/deaerator tank and is heated by bleed steam. Sodium sulfite, sodium phosphate, and tannin are added to the feedwater via a ball feeder valve. This system is typical of many of the boilers providing steam to shore facilities and ships.

Steam enters the boiler export line and flows to experimental stations (Figure 8). The boiler steam demand generally varies from 500 to 3,000 lbm/hr, and pressures are adjusted from 50 to 125 psig. In these tests, the steam flow rate ranged from 500 to 1,000 lbm/hr at pressures of 50 to 125 psig.

Experimental Model

Earlier testing and analysis suggested the need for generating a liquid film at low velocity, low turbulence, and maximum residence time. This would ensure a liquid boundary velocity less than the sputtering velocity (Ref 9), a minimum of liquid film entrainment into the free stream, minimal absorption, and time for deabsorption or degassing of carbon dioxide under a condition of thermodynamic nonequilibrium (Ref 10).

In an attempt to achieve these attributes, a system was devised (Figure 9) that consists of a single-pass, straight-tube, counterflow heat exchanger, vertically mounted with the outlet proceeding to a cyclonic separator. Steam entering the heat exchanger encounters an enlarged flow area (approximately 4 times larger) and drops in velocity. A circumferential liquid film develops, due to the coolant flow, and grows in the direction of gravity until exiting the tubes. Counter coolant water flow efficiently produces and controls liquid film growth. The two-phase liquid and gas then flow to the cyclonic separator where it effectively splits the liquid from the vapor (Ref 3 and 11). The fluid streams are then chemically analyzed after cooling. Both the entering and exiting fluid streams of the system are monitored for pH, conductivity, mass flow rates, and temperatures for a range of operating conditions.

It was found that impure boiler steam (pH ~4; conductivity ~13 $\mu\text{mho/cm}$) could be separated to produce a substantially more impure vapor stream (pH ~3.8; conductivity ~30 $\mu\text{mho/cm}$), but an even more pure liquid stream (pH ~6.5; conductivity ~2 $\mu\text{mho/cm}$). Indeed, this pure fluid generation proved to be sustained over a range of low liquid film production (10 percent of incoming flow) to very high film production (80 percent of incoming flow), as is revealed in Figure 10. The conductivity and pH of the purified stream remain near 2 $\mu\text{mho/cm}$ and 6.5, respectively, over the extreme flow conditions imposed. Expressed another way, the entering stream of near 100-ppm carbon dioxide can be reduced to less than 1 ppm (Figure 6), an astonishingly low amount.

Conceptual Model

The purified liquid has no value to ship boiler blanketing unless it becomes purified steam. A simple way of doing this is to have the available steam heat the pure liquid to saturated steam. The pure liquid could, at the same time, cool the incoming steam and produce the liquid film (Figure 11a). The system has all the properties of the experimental model (Figure 10), but uniquely reroutes the pure liquid back to the shell side of the heat exchanger for cooling purposes. This system is termed the Inverse Flash Steam Purifier, as it condenses the impure steam, produces flashing and evaporation to achieve the purified steam.

For this self-steam generator system to work, there must be a pressure variation between the tube side and shell side of the heat exchanger. Since the shell side pressure must be less than the tube side, then the corresponding saturation temperature will be similarly less. This liquid with its lower temperature then cools the incoming steam, but becomes heated to near saturation before exiting in counter-flow. A pressure reducing device (e.g., orifice, valve) will help control the production of pure impure steam.

This system was constructed as shown in Figure 11b. To determine the purity of the steam exiting the inverse flash system, the total exported steam at each exit was condensed and analyzed for pH, conductivity, and carbon dioxide (Figure 12). The inverse flash concept reduced the incoming levels of carbon dioxide from near 100 ppm to less than 3. This is judged quite acceptable, as it was only necessary to drop the level to near 10 ppm (Figure 6). The thermodynamic quality of the steam produced is just as important; steam that is too wet is ineffective and inefficient. The actual quality of the steam produced by the unit (shown in Figure 12) was very acceptable with levels greater than 95 percent.

Steam quality was determined by an energy balance of the condensing heat exchanger (Appendix B). The quality was verified in two ways. One was to change the system operating conditions until superheated steam could be produced (e.g., $p = 73$ psig, $t_{\text{sat}} = 306$ °F, $t_{\text{steam}} = 308.6$ °F or 2.6 °F superheat). The second way was to use an Ellison throttling calorimeter. Both methods verified the system performance (Figure 12b).

The impure vapor side was also condensed and analyzed. A clear plastic rotometer (used for flow rate measurement) revealed a near continuous line of bubbles (Appendix B). These bubbles have also been observed in the field when condensing shore steam for analysis. They are bubbles of carbon dioxide, and their existence suggest that they are unable to be absorbed by the already supersaturated liquid. The actual carbon dioxide levels were determined by inference methods (conductivity and pH) and verified by titration (Appendix B).

In review, the performance of the inverse flash steam purifier concept (Figure 12) appears to be quite good over a wide range of flow rates. Should an improvement in performance or range be necessary, it is possible to cascade units (Appendix C). Theoretically, units may be added until the carbon dioxide rich steam is predominantly carbon dioxide.

CONCLUSIONS

The great expense required to produce pure shore steam for ship boilers necessitates investigative efforts into more promising methods and concepts. Purifying nearly 100 percent of shore steam for ship boilers, that require only 5 percent of the total, offers an enormous cost saving opportunity.

1. The two-phase impure steam flow effort resulted in a concept that provides a steam-side treatment alternative to current feedwater treatment. It may be installed in the steam distribution system to passively separate the low pH-causing contaminant, carbon dioxide, from the steam, thus allowing the purified steam to continue to the ship boiler and the carbon-dioxide-rich steam to proceed to areas not having the NSTM clean steam requirements (Table 1).

2. The steam purification concept (Figure 11) is called an Inverse Flash Steam Purifier (IFSP). Impure steam is partially condensed in a vertical, single-pass, counterflow heat exchanger that maintains a low velocity, low-turbulence and film transport environment. The pure liquid is separated from the impure vapor using a cyclone separator. The liquid's pressure is slightly reduced and conveyed back to the heat exchanger where, by using it as a coolant for the shore steam, it is regenerated to a saturated vapor or even superheated level, if required.

The potential attributes of the Inverse Flash Steam Purifier are:

- Small, simple, and passive
- No electrical power requirements
- Carbon dioxide reduction >98 percent or at least two orders of magnitude
- High thermodynamic steam quality (>98 percent or superheat)
- High thermal efficiency (>98 percent)

3. The goal of the effort was to develop a steam side system concept and reduce the carbon dioxide levels by 82.5 percent without reducing neutralizing amines. The goal was achieved (>98 percent carbon dioxide reduction) by the IFSP concept. Steam with a high concentration of carbon dioxide needs only to be reduced to 8 ppm or less (Figure 6) to produce NSTM quality steam. The IFSP had little difficulty reducing carbon dioxide levels to less than 2.5 ppm (Figure 12).

4. While a factor of 100 can be expected in reducing the level of carbon dioxide with the IFSP, even greater reduction rates can be expected by cascading the units. For example, a cascade of six could reduce the level by 600 (Appendix C).

5. The investigation also revealed that saturated steam flow conditions (e.g., shore Navy steam distribution systems) provide a liquid film on pipe walls that possess a near neutral pH (7) and extremely low conductivities ($<2 \mu\text{mho/cm}$). This exists in spite of a very impure liquid core (Figures 2, 3, and 4). The situation exists as long as the distribution system is pressurized ($>100 \text{ psig}$). Should pressure be reduced, carbon dioxide is absorbed in the liquid film to produce a very acidic fluid (pH ~ 4) that results in corrosion.

RECOMMENDATIONS

A concept was devised and experimentally tested in the NCEL Steam Laboratory that revealed very promising performance characteristics. However, there are critical features to be examined for an eventual field deployment:

- General system performance in field conditions.
- Dynamic stability of the concept operating in a highly transient steam distribution system.
- Technical and economic feasibility of the concept when operating at the ship, the pier, the port header, or the steam plant.
- Neutralizing amine requirements when used with the concept.

We recommend the above analytical and test efforts be pursued as a 6.2 program. The cost benefit potential of the IFSP is significant.

ACKNOWLEDGMENTS

This effort would not have been possible without the contributions of Dr. J. Banerjee (UCSB Professor and Chairman of the Chemical and Nuclear Engineering Department), and experimenters R. Lovo and M. Silbernagel (EMC Corporation, Camarillo, CA.).

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LIST OF SYMBOLS

C_v	= control valve
f	= fugacity
F_m	= flow meter
H	= Henry's law constant
\dot{m}	= mass flow rate
Hx	= heat exchanger
M_{i-1}	= mass flow rate of purified stream
N_j	= mass flow rate of CO_2 enriched stream
P	= pressure
r	= recovery factor
R	= gas constant
T	= temperature
V	= free stream velocity
V_p	= port velocity
x	= weight fraction of CO_2 in enriched stream
X	= mole fraction in liquid phase of component i
y	= weight fraction of CO_2 in purified stream
z	= weight fraction of CO_2 in feed stream
Z_1	= feed stream flow rate
α	= separation factor
β	= heads separation factor
δ	= inverse separation factor
ϵ	= enrichment factor

γ = activity coefficient
 v = molar volume
 ϕ = fugacity coefficient
 w = depletion factor

Subscripts

c = critical state
 CO_2 = carbon dioxide
 H_2O = water
 i = specie
 j = phase
 M = mixture

Superscripts

L = liquid phase
 OL = standard state
 r = reference
 V = vapor phase
 $*$ = ideal dilute

Table 1. NAVSEA Steam Purity Criteria*

220-22.13 SHORE STEAM AND CONDENSED SHORE STEAM USED AS FEEDWATER.

Steam supplied directly to ships or condensed for use as feedwater shall be generated from feedwater which is either treated with a chemical oxygen scavenger or mechanically deaerated a maximum dissolved oxygen content of 15 ppb. Shore steam and condensed shore steam used as feedwater shall meet the following requirements:

Constituent or Property	Requirement
pH	8.0 to 9.5
Conductivity	25 μ mho/cm (25 μ S/cm)max
Dissolved Silica	0.2 ppm (0.2 mg/L)max
Hardness	0.10 apm (0.10 meq/L)max

Note: The use of filming amines to control steam/condensate pH is prohibited. Compliance with environmental and health regulations is the responsibility of the shore facility.

*NAVSEA S9086-GX-STM-020/CH-220 V2 R3

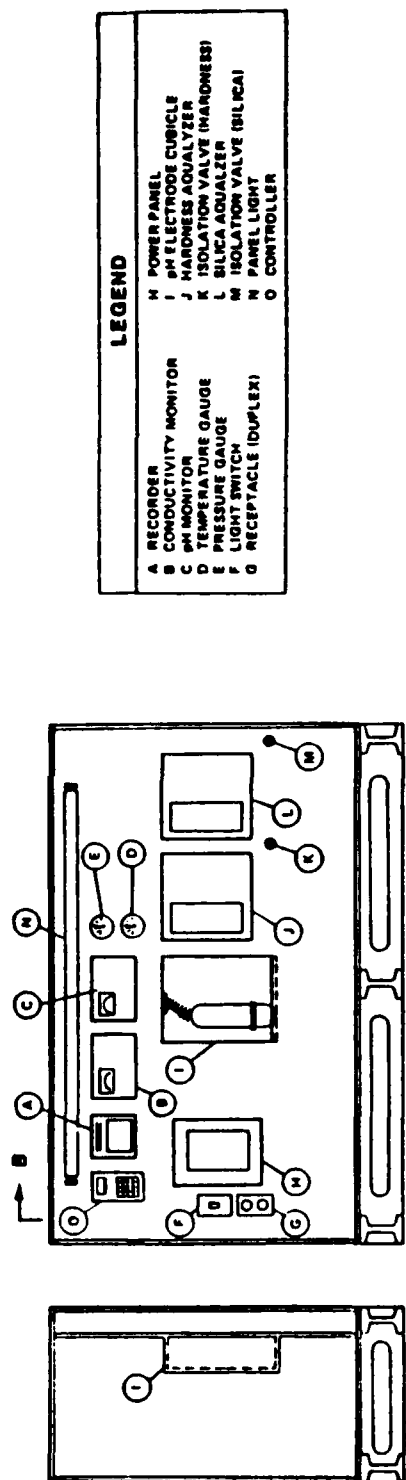
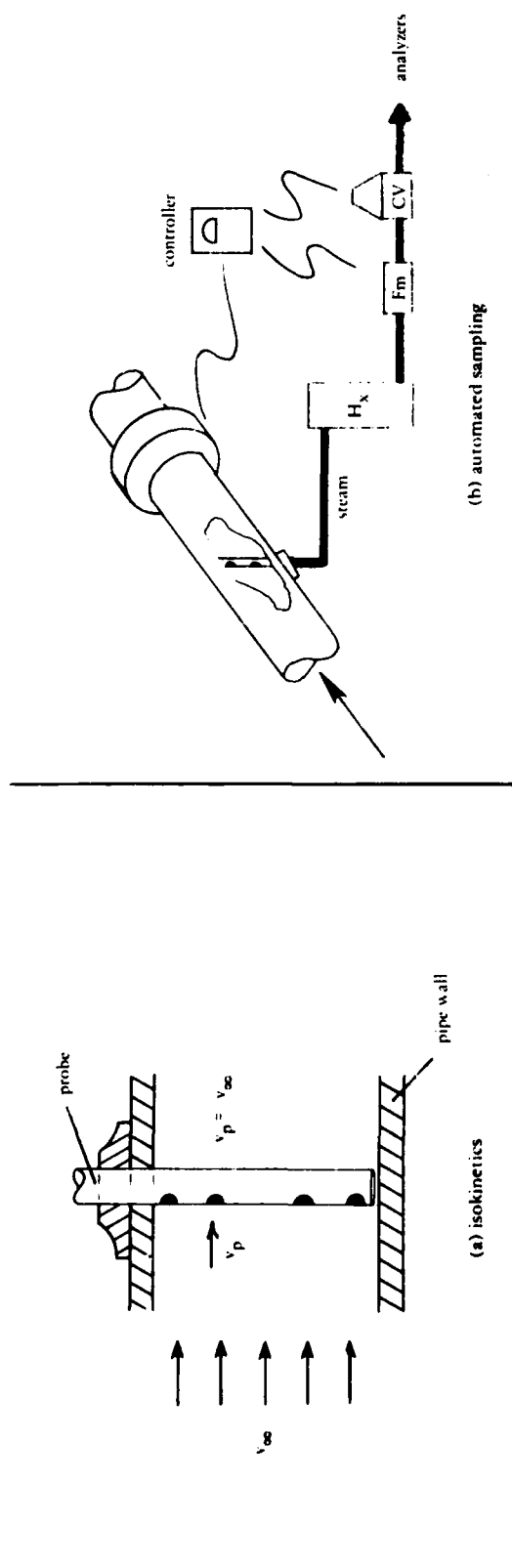


Figure 1. Isokinetic sampling data acquisition.

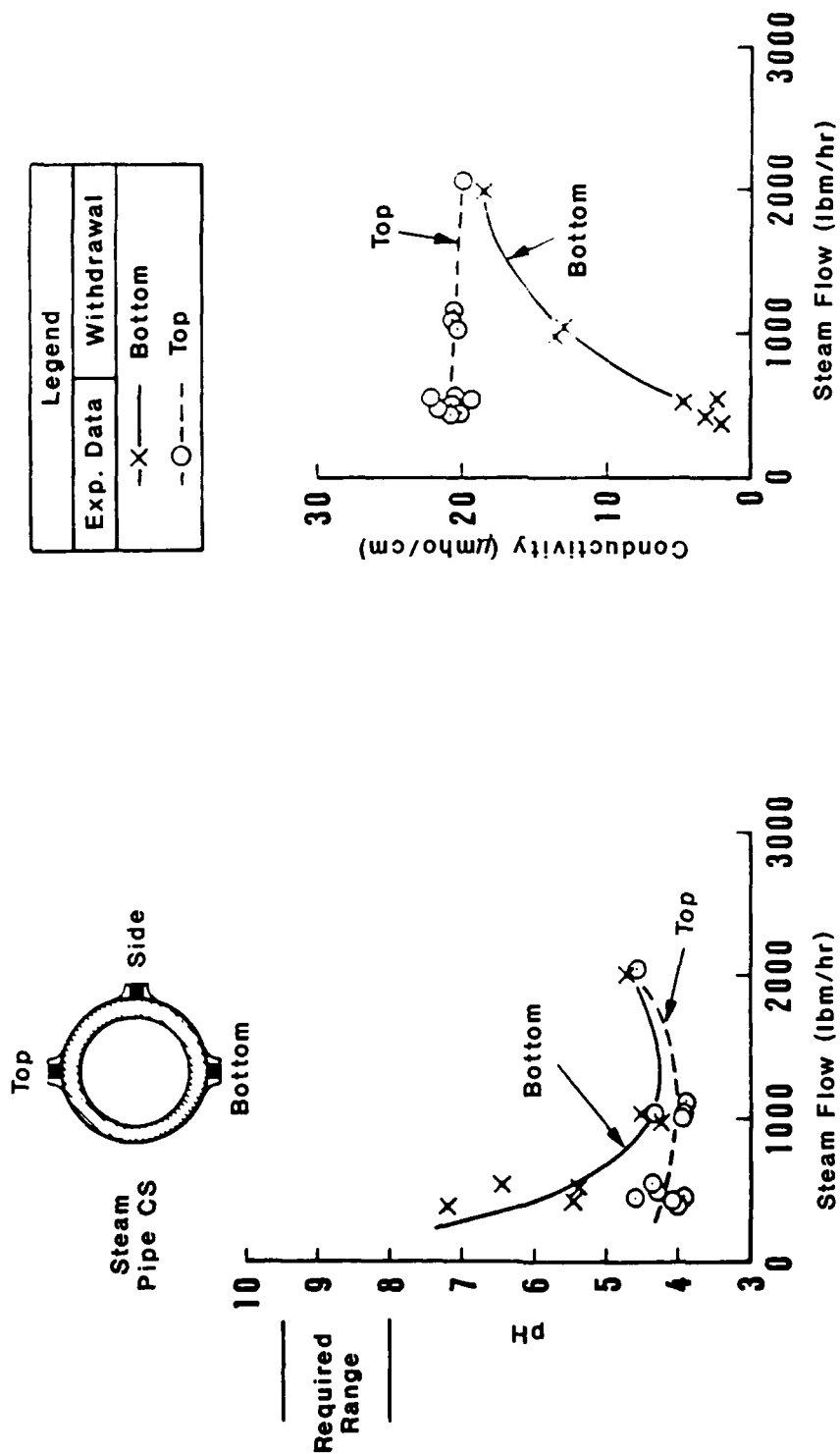


Figure 2. Boundary impurity level behavior.

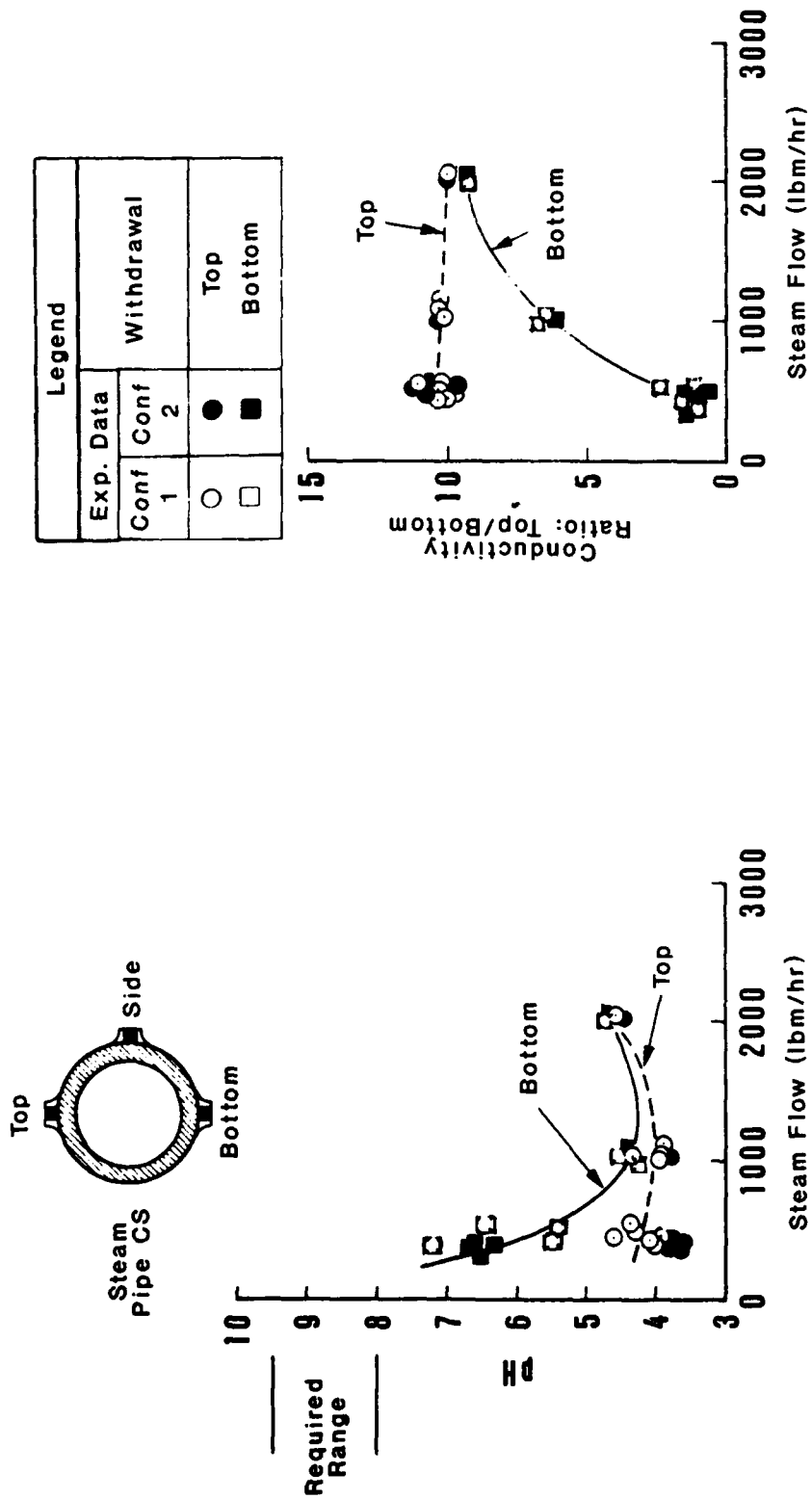


Figure 3. Boundary impurity independent of configuration.

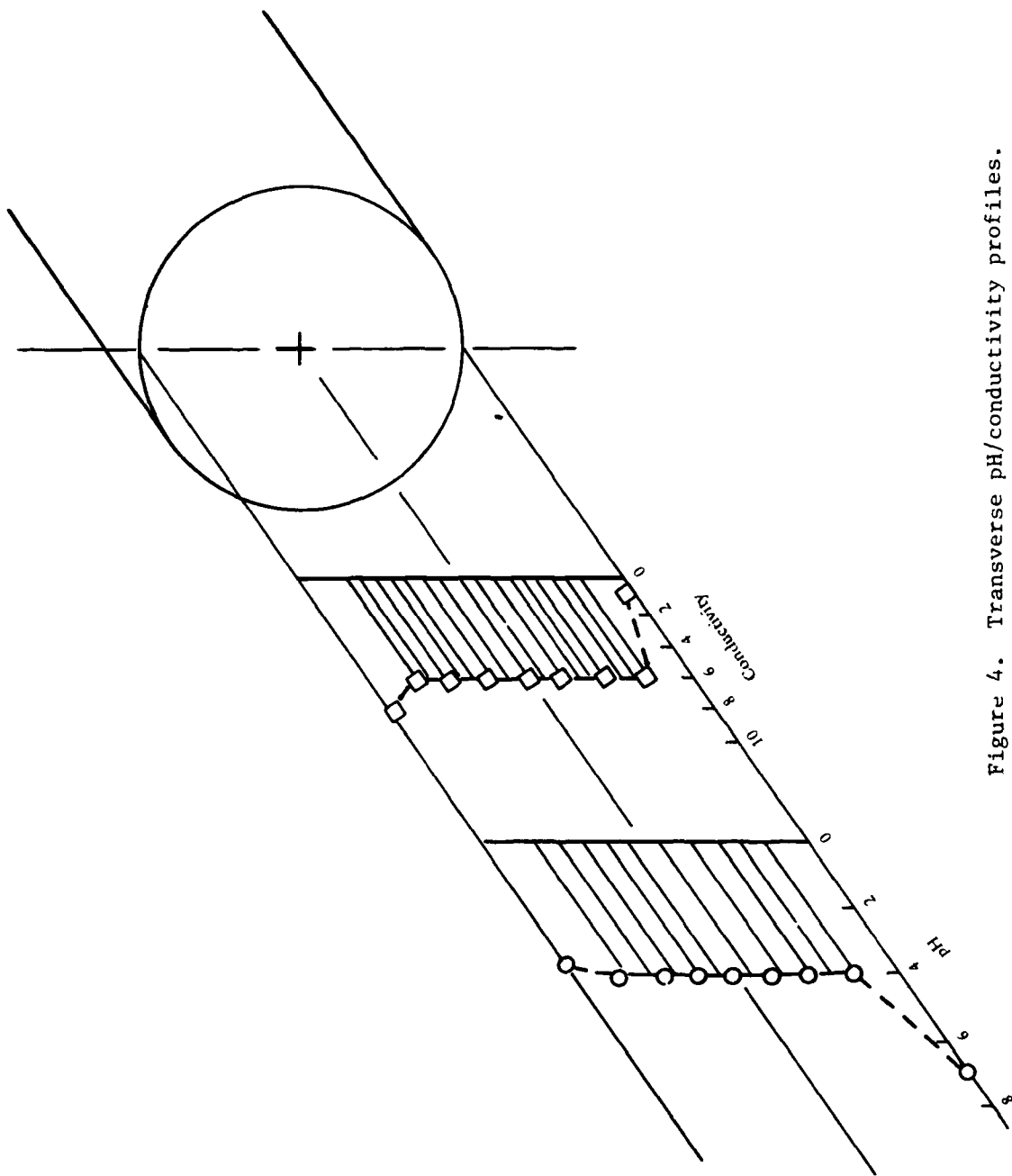


Figure 4. Transverse pH/conductivity profiles.

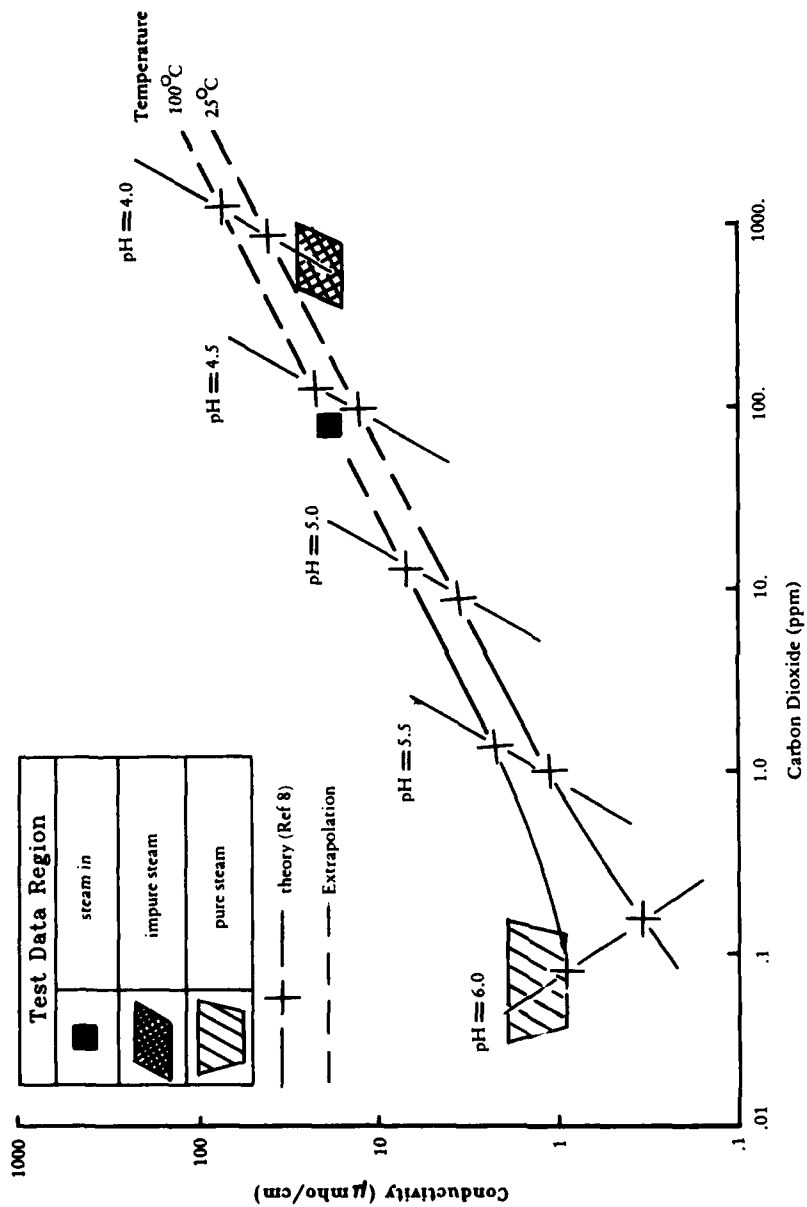


Figure 5. Relationship of carbon dioxide with pH/conductivity.

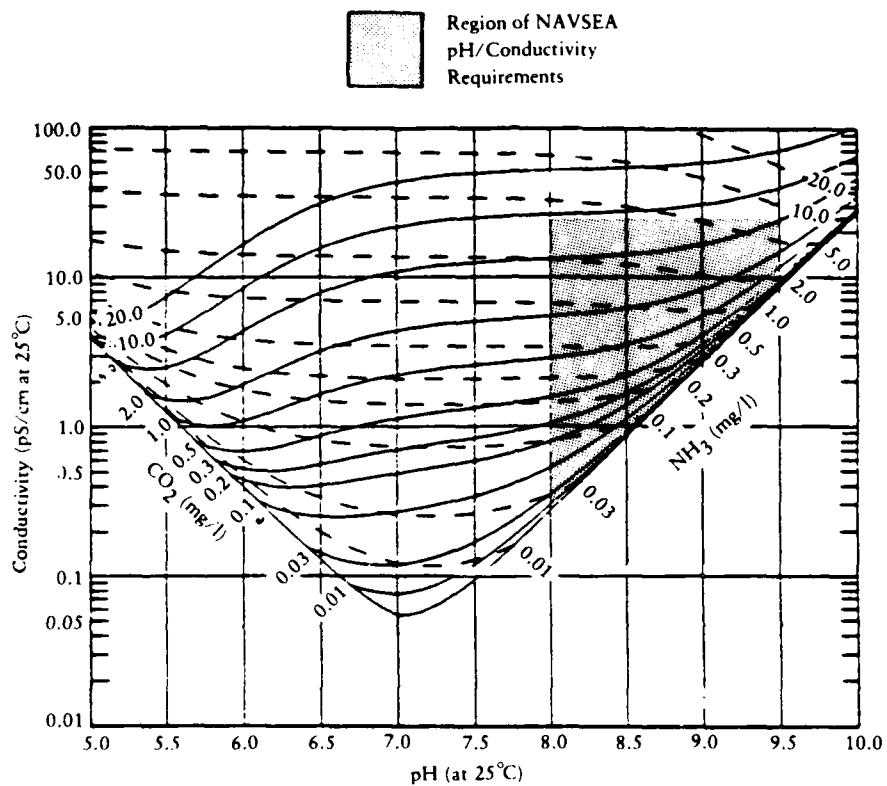


Figure 6. Relationship of CO₂/ammonia concentration to pH and conductivity (Ref 7).

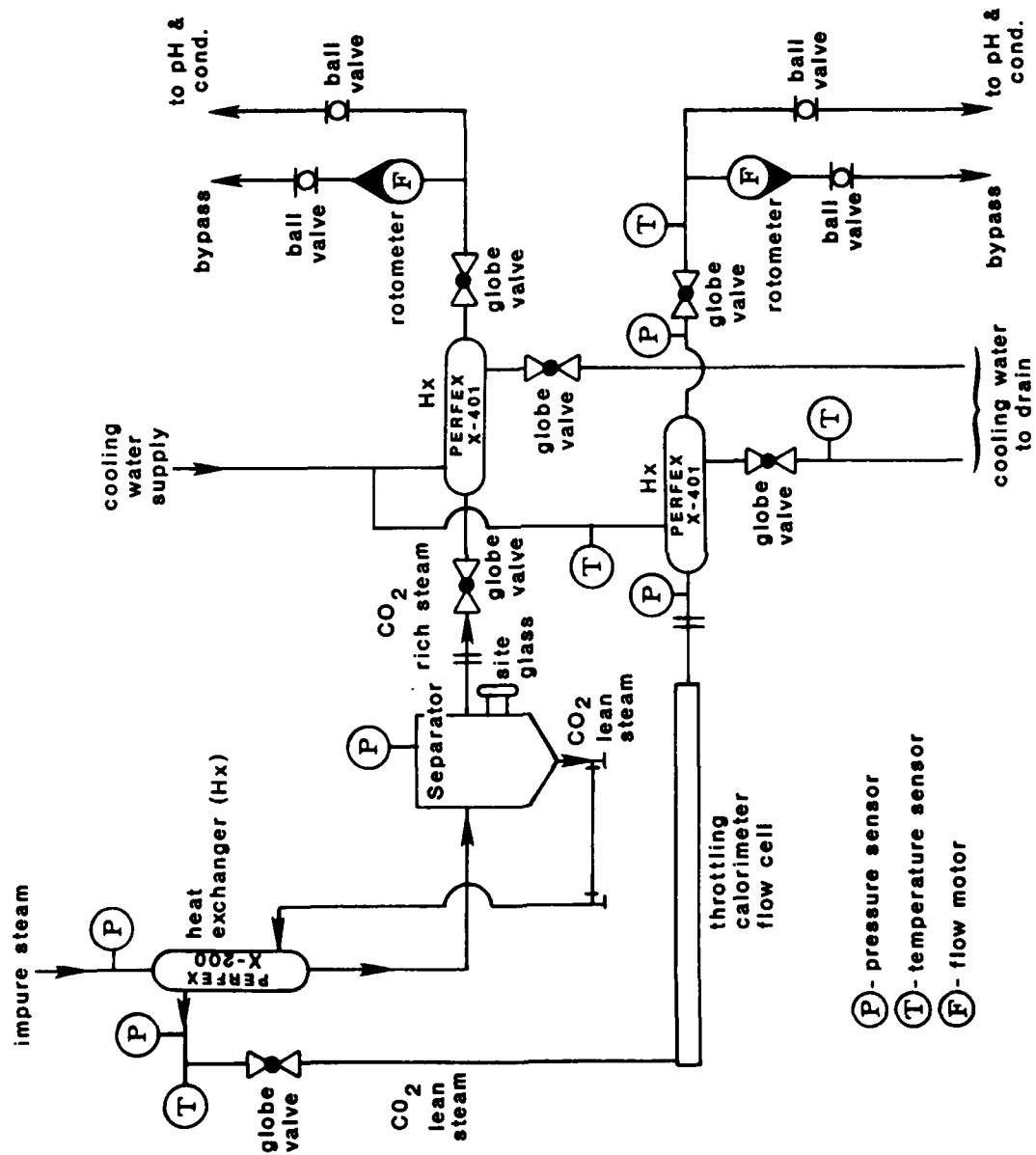


Figure 8. Experimental apparatus schematic.

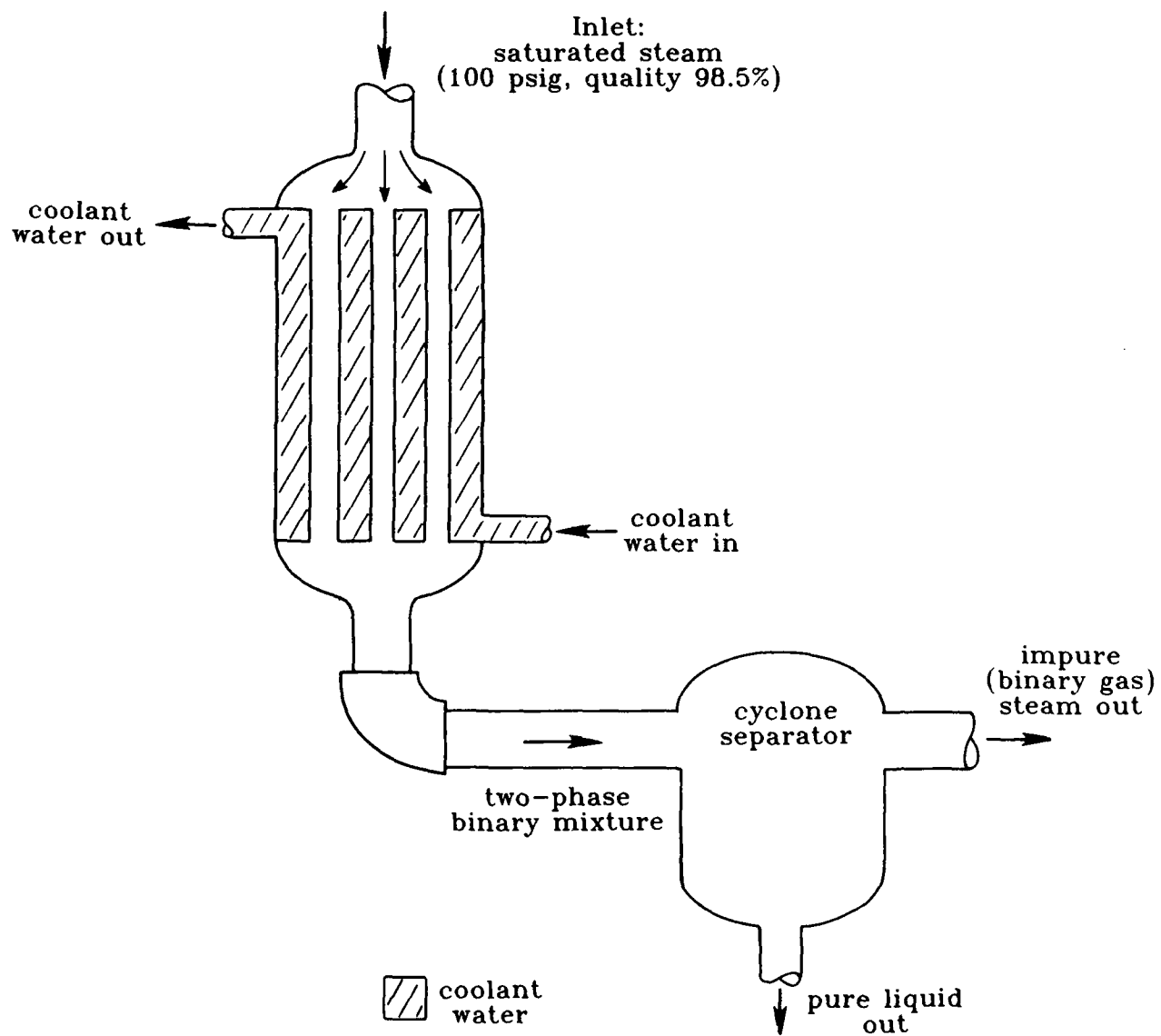


Figure 9. Experimental model for carbon dioxide separation.

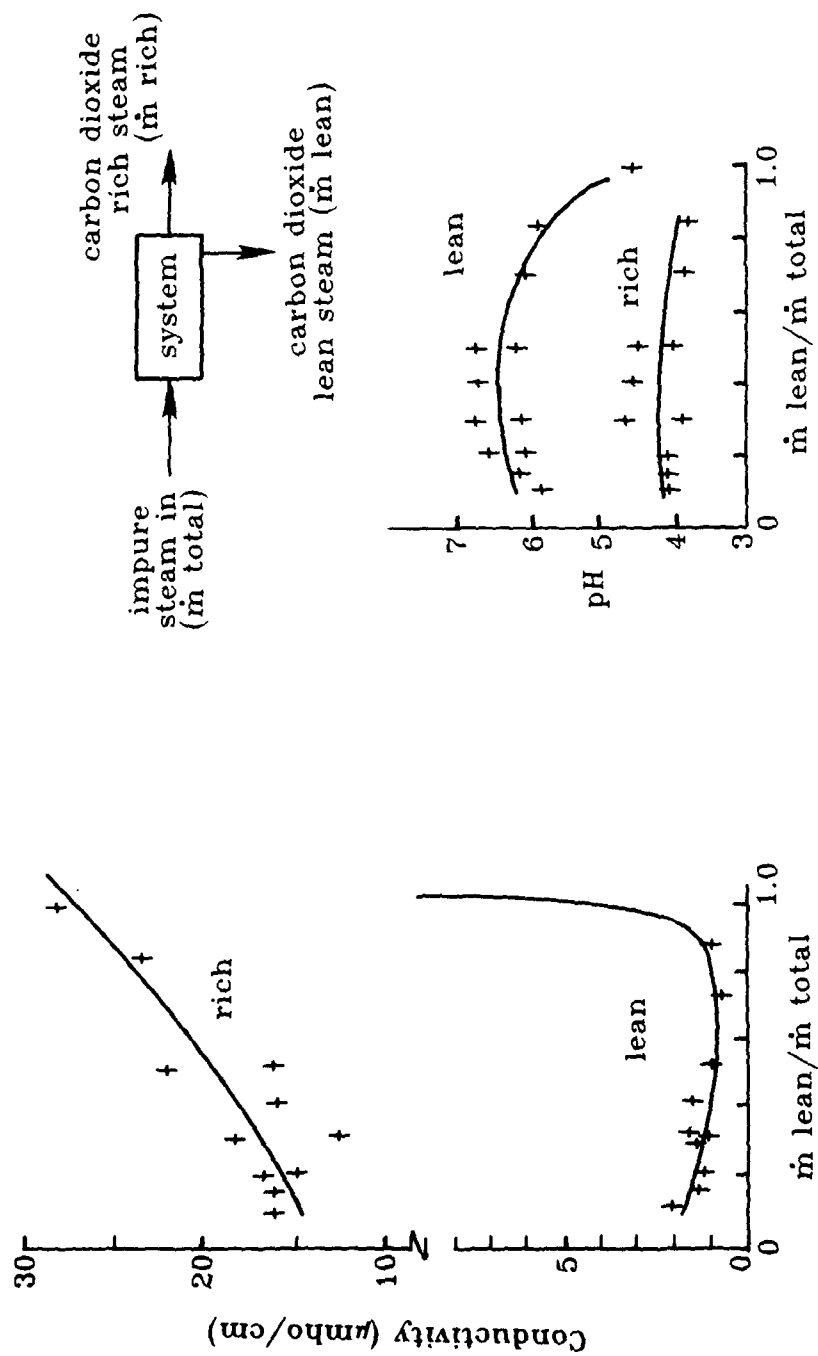
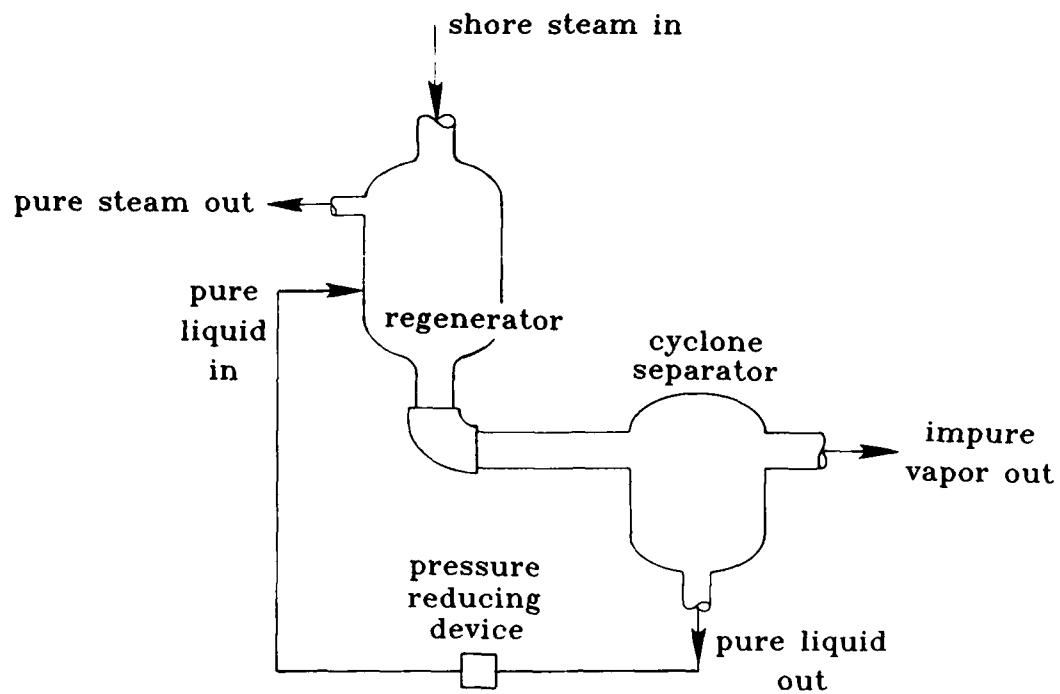
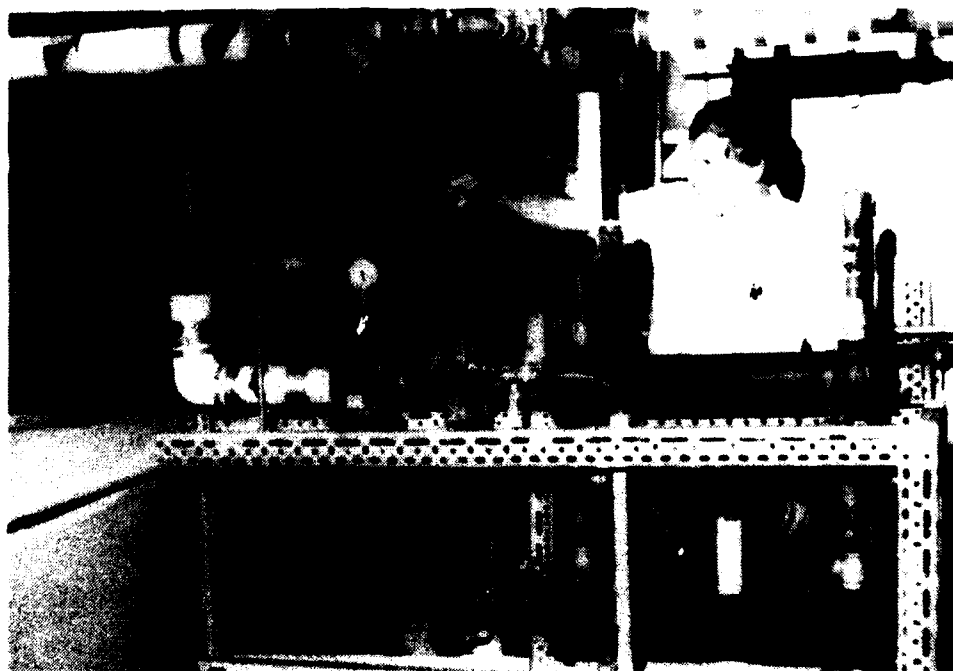


Figure 10. Experimental model data showing purity improvement.



(a) Schematic



(b) Laboratory system

Figure 11. Inverse Flash Steam Purifier concept.

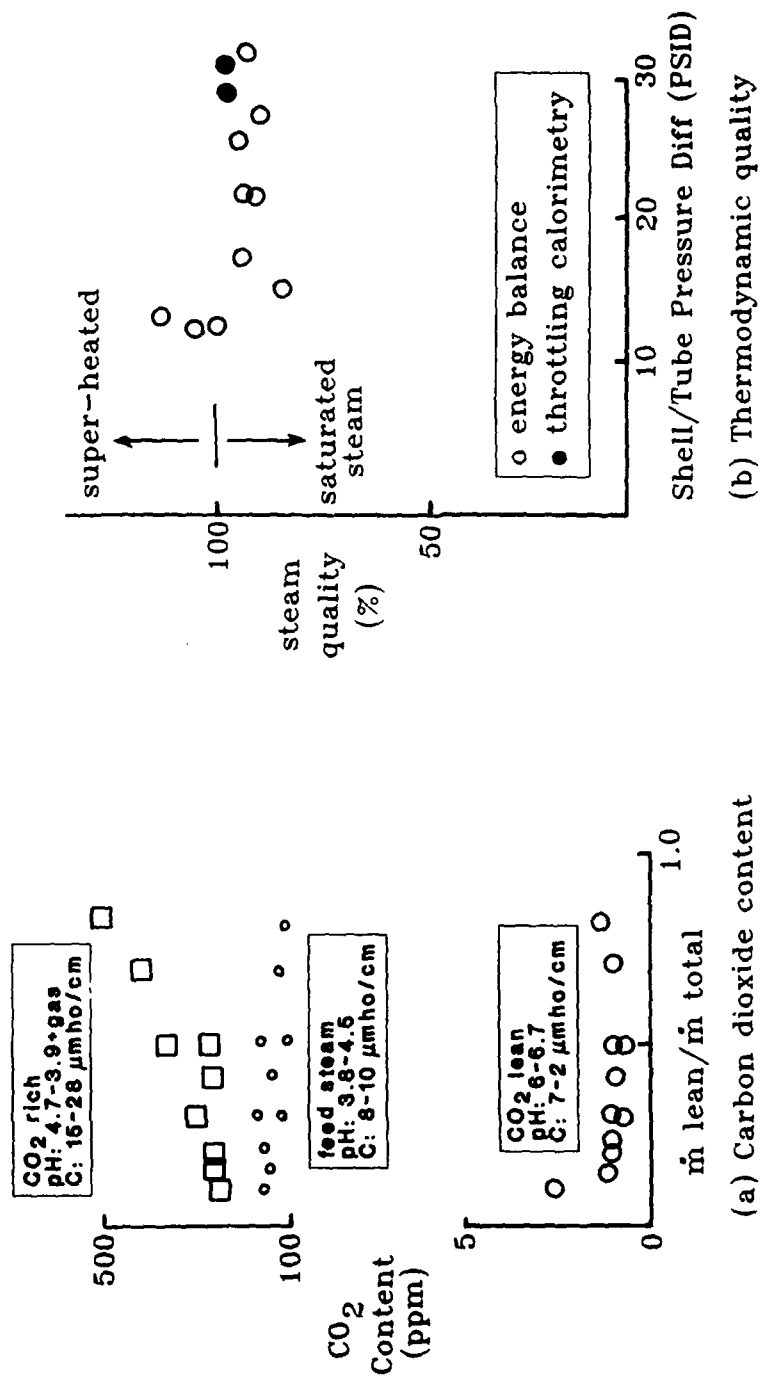


Figure 12. Inverse flash concept performance.

Appendix A

TEST NETWORK CONFIGURATION AND INSTRUMENTATION

CONFIGURATION 1

The configuration illustrated in Figure A-1 represents experimental testing for the isokenetic sampling (Ref 4-7). It was these tests where wall boundary purity observations were first noted. Pertinent test data are shown in Appendix B.

CONFIGURATION 2

Test Stand Installation

Testing of the Inverse Flash Steam Purifier (IFSP) was conducted at the NCEL Steam Laboratory. The Steam Lab is equipped with a rated 5,000-lb/hr, low-pressure boiler for the operation and testing of steam-related devices and equipment.

Several 3-inch-diam steam lines are provided for the setup of test systems. One of these lines was utilized for the IFSP testing. A diagram of the test installation is shown in Figure A-2. A summary of the components that comprise the test stand is presented in Table A-1.

Saturated steam at 0-150 psig is delivered through the 3-inch-diam main line to a 2-inch-diam test run. The 2-inch-diam test run provides the following:

1. Steam withdrawal through a 1-inch-diam line to feed the IFSP.
2. Orifice meter for monitoring flow in the 2-inch-diam line according to ASME standard methods.
3. Sample withdrawal at various circumferential locations on the pipe.
4. Sample withdrawal at isokenetic conditions.
5. Continuous monitoring of mainline steam flow, and sampling of pH, conductivity, silica content, and total hardness with the Steam Purity Monitoring System (SPMS).
6. Condensation of steam in the 2-inch-diam line for return to the boiler feedwater tank.

The 2-inch-diam line is approximately 20 feet long with flow control both upstream and downstream of the test run. The test run is insulated with 1-1/2 inches of fiberglass insulation.

Instrumentation

Instrumentation definition and characteristics are crucial to the measurement of steam purity. The instruments used were thoroughly tested, calibrated, and used according to ASTM standards (Ref 8).

The Steam Purity Monitoring System that was developed by NCEL (Ref 7) was used for the experimentation. This system contains continuous, in-line pH and conductivity meters, silica and hardness analyzers (pump-driven reagents from contamination-protected bottles), an automated isokenetic sampling system, a strip chart recorder, compact heat exchangers for steam cooling, safety bypass solenoid valves, and electrical and plumbing hardware to support the system (Figure A-3). All the apparatus are mounted in a 6 x 4 x 2-ft enclosure, having a total weight of less than 750 pounds. The enclosure allows portability and provides physical security and environmental protection. The system is self-contained, but requires 120-V electrical, <10-gpm water, and drain lines. Equipment positions and associated networking are shown in Figures A-4 and A-5.

Table A-1. Components of Steam Lab Test Installation

Component	Description
Steam test run	Approximately 22 feet of 2-inch-diam carbon steel pipe insulated with fiberglass.
Mainline steam trap	Armstrong inverted bucket-type trap for removing condensate from the 3-inch-diam mainline.
Steam Purity Monitoring System (SPMS)	Prototype monitoring system for continuously monitoring pH, conductivity, silica, and total hardness.
Isokenetic Sampling System (ISS)	Sampling system for the SPMS which maintains isokenetic flow conditions at the sampling probe.
Orifice meter	Two-inch-diam flange tap orifice meter with 1.625-inch-diameter stainless steel orifice plate. 20 inches of straight pipe upstream, and 4 inches downstream. Nearest fittings are unions. Two pressure transducers with 0-5-volt outputs provide signals to the ISS steam flow measurement.
Sampling ports	Five sampling ports, including three wall locations and two isokenetic sampling ports. Wall sampling ports are in the top, bottom, and side. Isokenetic sampling ports allow for horizontal or vertical installation of the probe. All probes are designed according to ASTM standards. Sample lines are 3/8-inch-diam 316 stainless steel.
Condenser	Shell and tube heat exchanger, double pass, steam on shell side, cooling water in tubes. Capacity of 5000-7000 lbs/hr of low pressure steam. Cooling water supply is potable water at 65-70 °F.
Condensate return	Armstrong float and thermostatic type steam trap for preventing steam from flowing in the condensate return line.

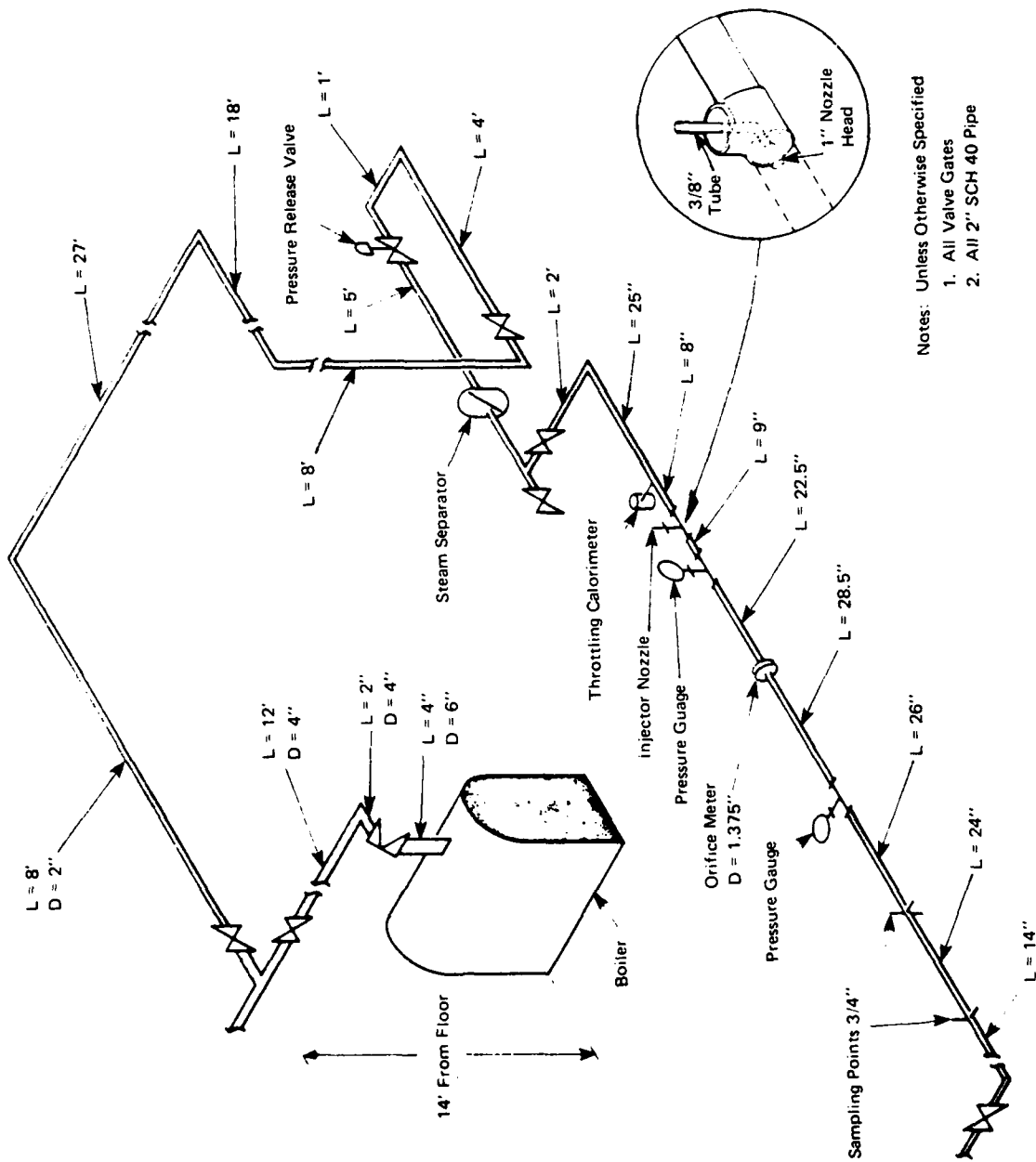


Figure A-1. NCEL boiler plant test set-up for (Configuration 1).

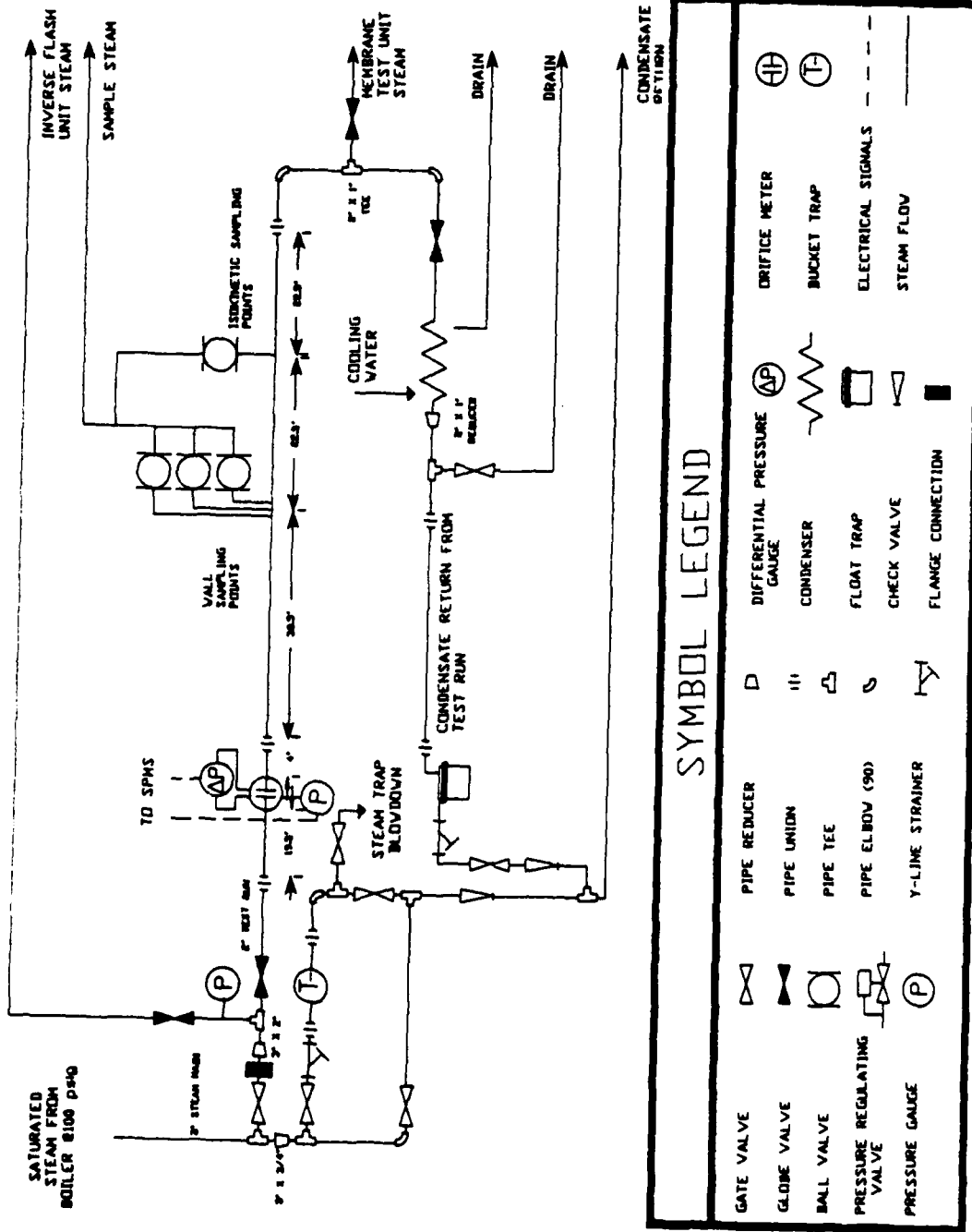
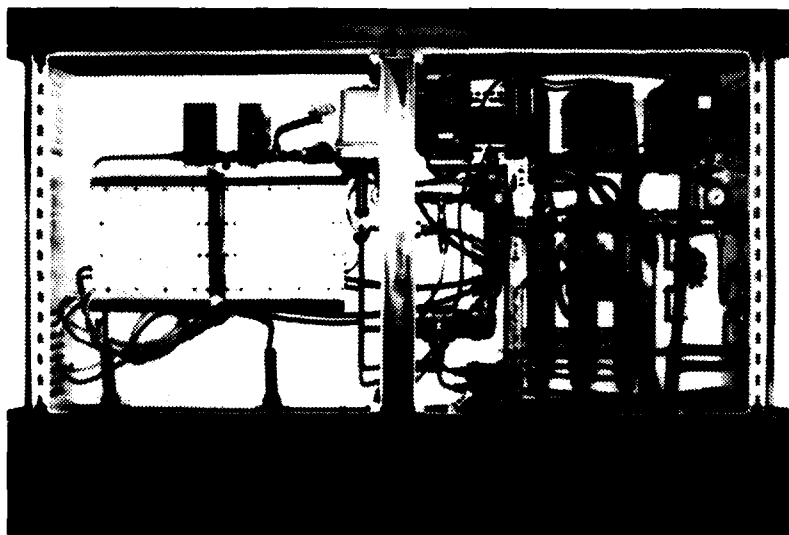


Figure A-2. Process and instrumentation diagram for NCEL steam lab test installation for CO₂ removal concepts.



a) front view



b) back view

Figure A-3. Steam purity measurement system.

LEGEND :

- | | |
|------------------------|------------------------------|
| A RECORDER | H POWER PANEL |
| B CONDUCTIVITY MONITOR | I pH ELECTRODE CUBICLE |
| C pH MONITOR | J HARDNESS AQUALYZER |
| D TEMPERATURE GAUGE | K ISOLATION VALVE (HARDNESS) |
| E PRESSURE GAUGE | L SILICA AQUALZER |
| F LIGHT SWITCH | M ISOLATION VALVE (SILICA) |
| G RECEPTACLE (DUPLEX) | N PANEL LIGHT |
| | O CONTROLLER |

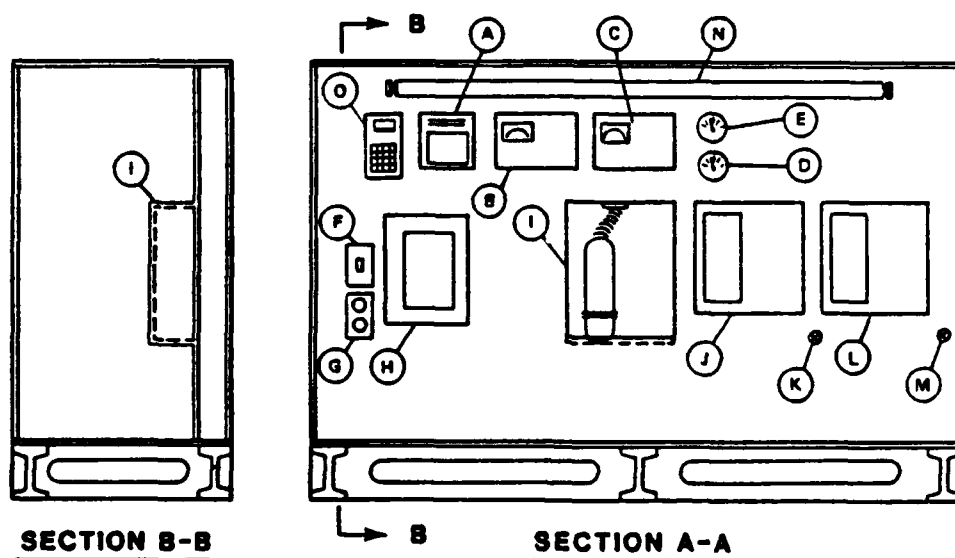


Figure A-4. Steam purity measurement system schematic.

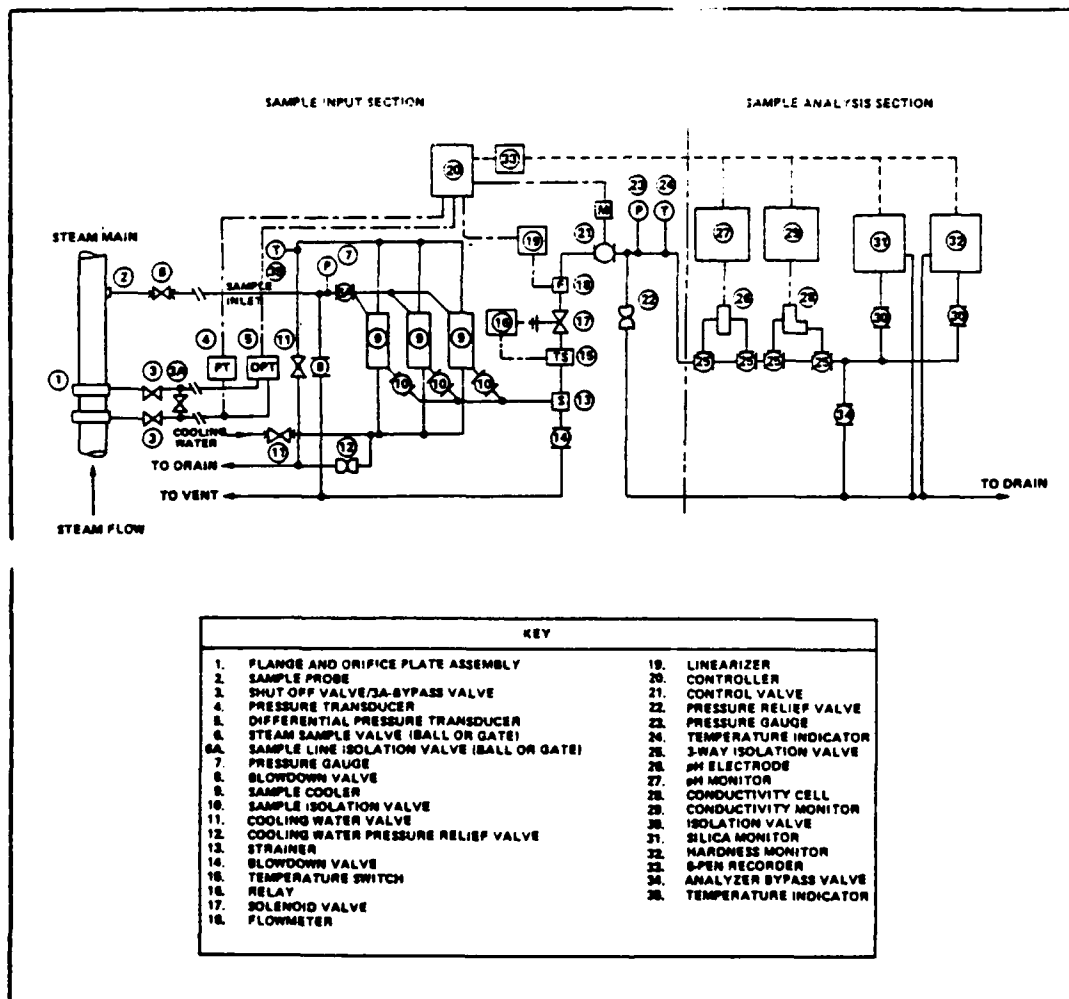


Figure A-5. SPMS process and instrumentation diagram.

Appendix B

TEST DATA

CONFIGURATION 1 TEST RESULTS

This configuration is identified in Appendix A and represents the Two-Phase Impure Steam tests that focused on isokinetic sampling (Ref 4-7).

These test results (Table B-1) are presented here to illustrate the wall boundary impurity levels first encountered.

CONFIGURATION 2 TEST RESULTS

The Inverse Flash Steam Purifier (IFSP) was tested for approximately 170 operating hours. During this period, certain operational parameters were measured and data (Table B-2) were collected. These include:

- IFSP separation pressure
- Energy transfer pressure
- Energy transfer temperature
- Rich stream flow rate
- Lean stream flow rate
- Cooling water inlet temperature
- Cooling water outlet temperature
- Cooling water flow rate
- Feed stream pH
- Feed stream conductivity
- Rich stream pH
- Rich stream conductivity
- Lean stream pH

- Lean stream conductivity
- Condenser stream pressure
- Condenser stream temperature

Collection of these data allowed a comprehensive evaluation of the IFSP performance in terms of carbon dioxide.

Typical Measurement Response

When a boundary condition was changed, as in switching from top sample withdrawal (impure steam) to bottom sample withdrawal (pure steam), it often required many hours for the system to reach steady state conditions. For example, 16 hours of running were necessary for the pH to level out (Figure B-1).

Solubility Comparisons

To estimate the performance that might be expected for the IFSP, the solubility properties were required. The only data found, which are shown in Figure B-2, were temperature and pressure limited. The options available were to linearly extrapolate the existing data or estimate through theoretical mean. The theoretical prediction, which is shown in the figure, does diverge from the extrapolation. A test data point seems to qualify the divergence from linearity. The theory and test data compare fairly well.

Carbon Dioxide Bubbling

When the carbon dioxide rich side of the IFSP is considered, the fluid originally comprised of water vapor and carbon dioxide gas becomes water with high levels of absorbed carbon dioxide (>600 ppm) and free carbon dioxide gas. The free carbon dioxide gas in bubble form (Figure B-3) is created because of the super condition of the carbon dioxide in the water.

Table B-1. Test Data for Configuration 1

Date	Time	Steam Flow (lbm/hr)	Iso Factor ¹	Config. ²	pH	Conductivity (µmbos)	Hardness (ppm)	SiO ₂ (ppm)
01/15/85	1130	561	1.0	B	6.4	2.0	0.9	-
	1317	571	1.0	T	4.3	20.5	0.65	-
	1400	554	1.0	B	5.3	4.5	1.5	-
	1444	561	1.0	T	4.3	20.5	0.65	-
01/18/85	0725	455	1.0	B	4.9	3.0	0.5	-
	0821	507	1.0	T	4.0	20.0	0.77	-
01/21/85	0920	942		T	3.95	20.0	0.5	0.0
	0953	942		B	4.15	13.5	0.12	0.19
01/22/85	0810	461		T	3.95	21.5	0.17	-
	0842	968		T	3.95	20.5	0.15	-
01/23/85	1300	992		T	3.9	20.8	0.14	0.085
02/01/85	1627	458		T	4.0	20.5	0.5	0.075
	1726	458		T	5.4	2.5	0.3	-
02/13/85	0800	942	1.0	PS	4.4	21.5	2.0	0.08
	0849	992	1.0	PS	4.35	22	1.65	0.05
	1009	992	1.0	B	4.5	13	1.2	0.22
	1128	992	1.0	T	4.4	22	1.95	0.065
	1232	1450		T	4.6	19.5	1.45	.075
	1334	1423		B	4.65	18.5	1.3	0.12
	1430	1385		PS	4.65	19.9	1.32	0.072
02/15/85	0700	450		PS	4.4	24	2.4	0.065
	0743	460		T	4.35	23.5	2.3	0.065
02/19/85	1231	500	1.0	B	7.2	1.7	Off Scale	0.245
	1302	500	1.0	T	4.6	19.0	>5.0	0.045
	1400	500	1.0		4.60	19.5	-	0.075
	1505	500	1.0		4.55	19.2	-	0.055

¹ Isokinetic factor = sample port withdrawal velocity/steam main velocity.

² B = Bottom sampling (no probe)
T = Top sampling (no probe)
S = Side sampling (no probe)
PS = Probe sampling, side mounted

Table B-2. Data Base for Inverse Flash Steam Purifier

Element	Laboratory Test				
	Run #1	Run #2	Run #3	Run #4	Run #5
Sep. Press (psig)	62	60	62	64	63
Hx Press (psig)	32	32	32	40	36
Hx Temp (°C)	137	138	139	144	141
Rich Flow (gpm)	0.495	0.495	0.495	0.511	0.528
Lean Flow (gpm)	0.223	0.228	0.203	0.238	0.216
Cooling In (°F)	67	67.5	68	67.5	68
Cooling Out (°F)	121	122	120	120	120
Cooling Flow (gpm)	4.07	4.07	4.05	4.05	4.05
Steam Quality * (%)	87.2	85.8	92.8	76.7	85.8

*Calculated

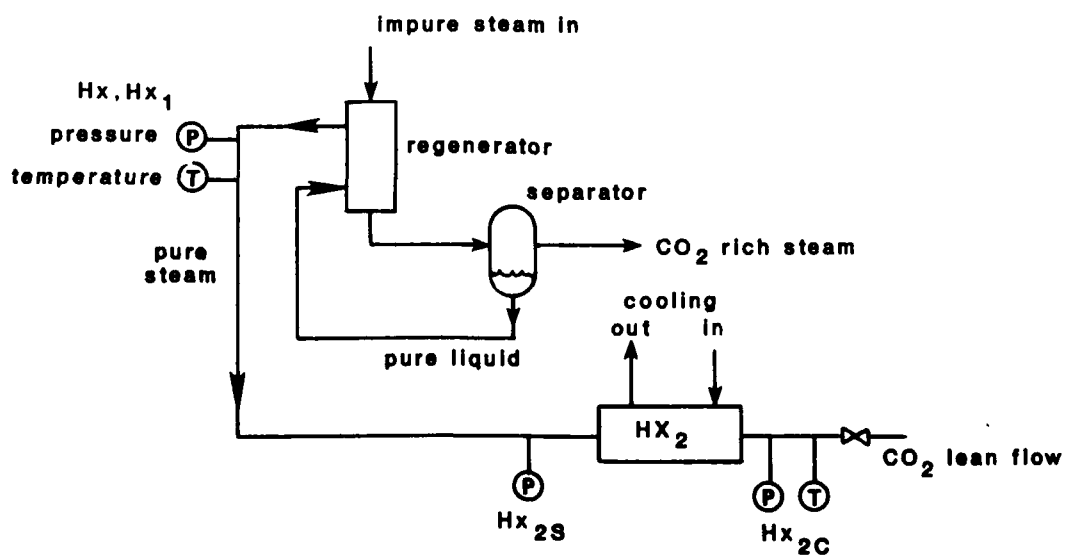


Table B-2. Continued

Element	Laboratory Test		
	Run #6	Run #7	Run #8
Sep. Press (psig)	40	44	30
Hx Press (psig)	21	21	10
Hx Temp (°C)	130	129	117
Rich Flow (gpm)	0.396	0.428	0.406
Lean Flow (gpm)	0.223	0.191	0.204
Cooling In (°F)	68	68	68
Cooling Out (°F)	116	115.5	117
Cooling Flow (gpm)	4.05	4.05	4.05
Steam Quality* (%)	75.7	90.1	87.4

*Calculated

Table B-2. Continued

Element	Laboratory Test				
	Run #9	Run #10	Run #11	Run #12	Run #13
Sep. Press (psig)	44	44	60	62	62
Hx ₁ Press (psig)	22	10	30	20	10
Hx ₁ Temp (°C)	128	125	135	126	115
Rich Flow (gpm)	0.453	0.488	0.587	0.587	0.587
Lean Flow (gpm)	0.220	0.149	0.225	0.237	0.291
Hx _{2s} Press (psig)	19	9.5	28.5	18.5	7.5
Hx _{2c} Press (psig)	19	9.5	28.5	18.5	7.5
Hx _{2c} Temp (°C)	36.5	33	36.5	36.5	38
Cooling In (°F)	68	68	68	68	68
Cooling Out (°F)	116.5	104	122	125.5	136
Cooling Flow (gpm)	4.43	4.43	4.38	4.38	4.38
Steam Quality (%)	87.1	97.7	94.5	96.3	93.0

*Calculated

Table B-2. Continued

Element	Laboratory Test				
	Run #14	Run #15	Run #16	Run #17	Run #18
Sep. Press (psig)	84	84	86	82	83
Hx ₁ Press (psig)	60	58	52	40	30
Hx ₁ Temp (°C)	157	154	152	144	137
Rich Flow (gpm)	0.689	0.660	0.689	0.660	0.660
Lean Flow (gpm)	0.138	0.125	0.203	0.260	0.260
Hx _{2s} Press (psig)	58.5	56	50	38	28
Hx _{2c} Press (psig)	58.5	56	50	38	28
Hx _{2c} Temp (°C)	36	36	38.5	41	40.5
Cooling In (°F)	69	68	68	69	69
Cooling Out (°F)	110	108	122	136	136
Cooling Flow (gpm)	3.95	3.95	3.95	3.95	3.90
Steam Quality (%)	106	106	93.5	97	98.9
Lean pH			6.1	6.4	6.25
Lean Conductivity			4.0	3.5	2.5
Rich pH			4.4	4.4	4.4
Rich Conductivity			16.0	16.0	16.0
Feed pH			4.5	4.5	-
Feed Conductivity			13.0	13.0	-

*Calculated

Table B-2. Continued

Element	Laboratory Test			
	Run #19	Run #20	Run #21	Run #22
Sep. Press (psig)	80	81	84	80
Hx ₁ Press (psig)	18	8	60	50
Hx ₁ Temp (°C)	126	113	161	150
Rich Flow (gpm)	0.660	0.660	0.689	0.660
Lean Flow (gpm)	0.244	0.240	0.137	0.220
Hx _{2s} Press (psig)	16	6	58	48
Hx _{2c} Press (psig)	16	6	58	48
Hx _{2c} TEMP (°C)	38	37	37	39
Cooling In (°F)	69	69	69	69
Cooling Out (°F)	130	126	106	121
Cooling Flow (gpm)	4.20	4.24	4.15	4.0
Steam Quality* (%)	95.5	91.3	100.6	82.2
Lean pH	6.2	6.35	6.05	6.7
Lean Conductivity	2.0	2.2	2.9	5.3
Rich pH	4.4	4.4	4.4	4.4
Rich Conductivity	16.0	15.0	15.5	14.5
Feed pH	4.5	4.5	4.5	4.5
Feed Conductivity	12.5	13.0	12	12.2

*Calculated

Table B-2. Continued .

Element	Laboratory Test			
	Run #23	Run #24	Run #25	Run #26
Sep. Press (psig)	80	81	84	80
Hx ₁ Press (psig)	40	30	20	9
Hx ₁ Temp (°C)	143	137	129	115
Rich Flow (gpm)	0.634	0.647	0.660	0.675
Lean Flow (gpm)	0.220	0.240	0.244	0.244
Hx _{2s} Press (psig)	38	28	18	7
Hx _{2c} Press (psig)	38	28	18	7
Hx _{2c} Temp (°C)	39	39	39.5	38
Cooling In (°F)	69	69	69	69
Cooling Out (°F)	126	130	136	132
Cooling Flow (gpm)	4.0	4.21	4.17	4.05
Steam Quality* (%)	92.5	96.7	105.3	95.5
Lean pH	6.6	6.35	6.35	6.30
Lean Conductivity	3.6	2.5	2.0	1.8
Rich pH	4.35	4.35	4.35	4.38
Rich Conductivity	15.2	14.0	14.5	13.9
Feed pH	4.5	4.5	4.5	4.5
Feed Conductivity	12.5	12.8	12.3	11.3

*Calculated

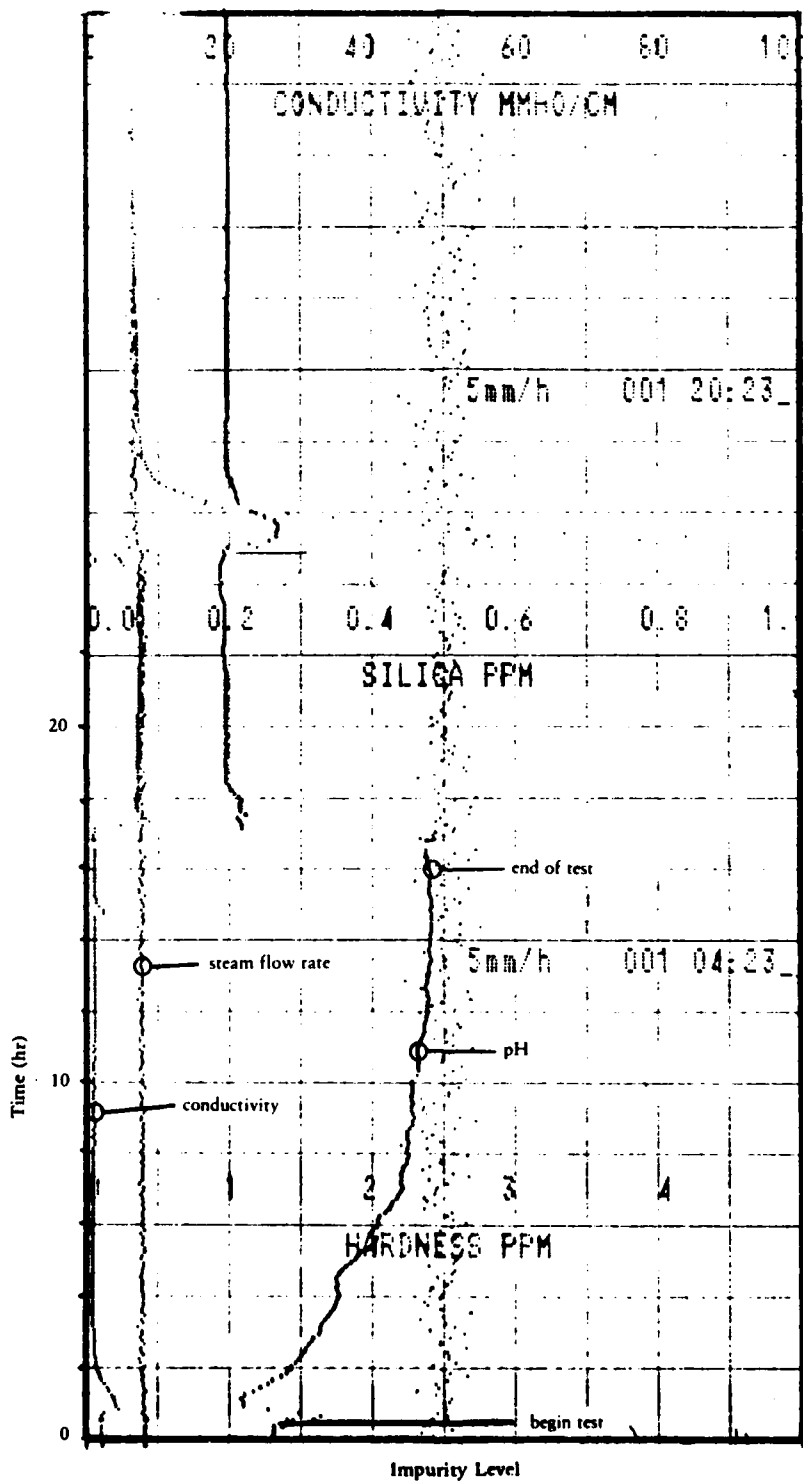


Figure B-1. Purity measurement response.

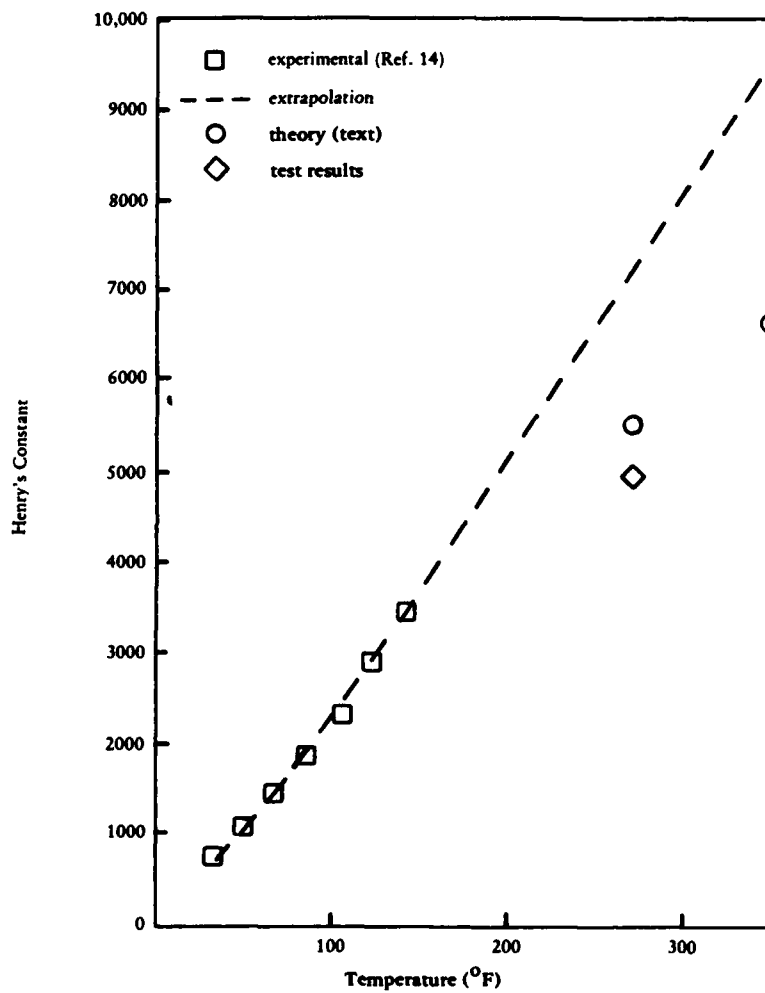


Figure B-2. Carbon dioxide versus water solubility.

Appendix C

A MULTISTAGE CASCADE ANALYSIS

A process with a large separation is desired. Separation factors are defined with reference to Figure C-1.

The separation factor, α , is defined as

$$\alpha = \frac{y/(1-y)}{x/(1-x)} = \frac{y}{x} \quad (C-1)$$

The heads separation factor, β , is defined as

$$\beta = \frac{y/(1-y)}{z/(1-z)} = \frac{y}{z} \quad (C-2)$$

Note that Equation C-2 is true for carbon dioxide concentrations that are low, i.e., x , y , and $z \ll 1.0$ when x , y , and z are the weight fraction of the carbon dioxide in each stream.

Thus, it is desired to find a simple process that will give small values of α and β as defined in Equation C-1 and C-2 or large values of $1/\alpha$ or $1/\beta$.

Consider the simple cascade sketched in Figure C-2. It is a system built from a number of stages modelled after the one shown in Figure C-1. In this case the "heads" refer to the carbon dioxide depleted stream as the product in carbon dioxide is depleted. The "tails" is the carbon dioxide enriched stream which is not desired. This is the simplest possible cascade with no further processing of the "tails" stream. If a very small quantity of "tails" is desired then more complex "recycle cascades" must be utilized. However, as the "tails" stream can be utilized for many purposes, it is not considered waste. Therefore, it is not required at present to reduce it to a very small quantity. In this case

$$z_i = M_{i-1} \quad (C-3)$$

That is, the heads (carbon dioxide depleted) stream from the $i-1$ slope is the feed for the i th stage. Also,

$$z_i = y_{i-1} \quad (C-4)$$

That is, the carbon dioxide concentration in the heads stream from the $i-1$ stage is the same as in the feed to the i th stage. Define the "recovery" from the i th stage as

$$r_i = \frac{M_i y_i}{Z_i z_i} \quad (C-5)$$

This "recovery" may be thought of as the ratio of the carbon dioxide outflow to the carbon dioxide inflow. We have, in addition (generally), the conservation of mass and the conservation of carbon dioxide

$$Z_i = M_i + N_i \quad (C-6)$$

$$Z_i z_i = M_i y_i + N_i x_i \quad (C-7)$$

From this it follows that

$$\frac{M_i}{Z_i} = \frac{z_i - x_i}{y_i - x_i} \quad (C-8)$$

Substituting in C-5

$$r_i = \frac{1 - (x_i/z_i)}{1 - (x_i/y_i)} = \frac{\alpha_i - \beta_i}{\alpha - 1} \quad (C-9)$$

from C-1 and C-2.

The "recovery" from n stages is

$$r = r_1 r_2 = r \dots r_n \quad (C-10)$$

The overall "depletion" or "enrichment" of carbon dioxide from n stages is

$$(\text{depletion factor}) \omega = \frac{y_n/(1 - y_n)}{z_1/(1 - z_1)} \quad (C-11)$$

$$(\text{enrichment factor}) \epsilon = 1/\omega$$

From the definition of the heads separation factor, β , (see Equation C-2), it follows that

$$\omega = \beta_1 \beta_2 \dots \beta_n \quad (C-12)$$

Consider each stage now similar to the other with temperatures and pressures very close to each other. Then

$$\begin{aligned} \alpha &= \alpha_1 = \alpha_2 \dots \alpha_n \\ \beta &= \beta_1 = \beta_2 \dots \beta_n \end{aligned} \quad (C-13)$$

and

$$\omega = \beta^n = y_n/z_1 \quad (C-14)$$

$$r = \left(\frac{\alpha - \omega^{1/n}}{\alpha - 1} \right)^n = \left[\frac{(a - y_n/z_1)^{1/n}}{\alpha - 1} \right]^n \quad (C-15)$$

Note that the overall recovery is also

$$r = \frac{M_n y_n}{Z_i z_i} \quad (C-16)$$

Therefore, there exists a relationship between the overall separation (in this case, depletion of carbon dioxide) in the cascade (y_n/z_1) and the mass flow rates of the feed and product streams (M_n/Z_1). The relationship is through Equation C-15.

Consider now a situation when the number of stages, n , is required to provide a specified depletion factor (y_n/z_1) of carbon dioxide and a specified product to feed flow rate ratio M_n/Z_1 . We then have the relationship

$$\left[\frac{\alpha - (y_n/z_1)^{1/n}}{\alpha - 1} \right]^n = \left(\frac{M_n}{Z_1} \right) \left(\frac{y_n}{z_1} \right) \quad (C-17)$$

In this equation α is known, y_n/z_1 is specified, and M_n/Z_1 is specified. The only unknown is n , which can be solved from Equation C-17.

For the cases considered in this report, $\alpha \ll 1$; so we may write Equation C-17 as

$$\left[\frac{(y_n/z_1)^{1/n} - \alpha}{1 - \alpha} \right]^n = \left(\frac{M_n}{Z_1} \right) \left(\frac{y_n}{z_1} \right) \quad (C-18)$$

Note that the "depletion" or "purification" factor, y_n/z_1 , is specified as well as the product (purified steam) to (input steam), M_n/Z_1 . Therefore n has to be determined.

We have tabulated in Table C-1 the minimum number of stages that will give $y_n/z_1 = 1/100$, i.e., purify say 300 ppm carbon dioxide down to 3 ppm carbon dioxide. For the membrane and cyclone, no (or infinitesimal) product is formed.

Table C-1. Minimum Number of Stages
for $y_n/z_1 = 1/100$

Method	n_{\min}	M_n/Z_1
Membrane	10	~0
Cyclone	13	~0
Flash (inverse)	1	0.845

Note that the inverse flash will give 85% purified steam in one stage with a purification factor of 100. Clearly high purities can be achieved with the inverse flash method while still producing a reasonable amount of product in one stage. Table C-2 gives some calculations for various purification factors.

It is clear that for most practical purposes, sufficient purification and flow rate of purified steam are obtained in one stage inverse flash. If higher flow rates of purified steam or higher purity is denied, more stages may be used.

Table C-2. Purity (y_n/z_1) versus Product Flow (M_n/Z_1)
for One-Stage Inverse Flash

Purity (ppm) (Outlet Steam CO_2 /Feed Steam CO_2)	Product Flow (Purified Steam/Feed Steam)
1/100	0.845
1/200	0.69
1/300	0.525
1/600	0.07

The inverse flash or condensation stage gives high purification and is desirable because of its simplicity and low cost. A practical embodiment may be a partial condenser and separator arrangement as shown in Figure C-3. Note that all the heat for flashing is supplied by condensation. Therefore, no net energy input is necessary. If more than one stage is desired for greater purification and greater pure steam flow rate, then the schematic in Figure C-6 indicates how this may be done. Note that all the heat for flashing is supplied by the condensation side.

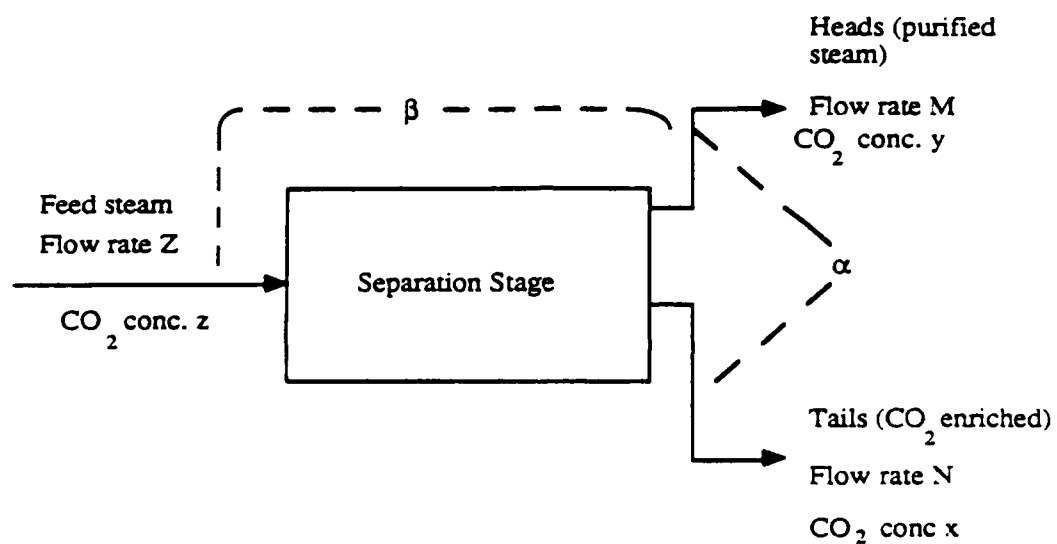


Figure C-1. Flow rates, compositions, and separation factors in a separating stage.

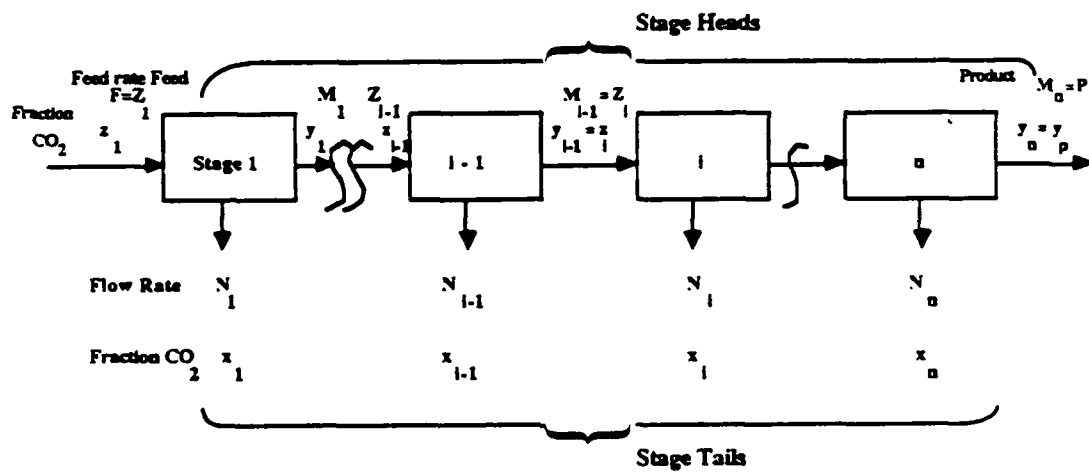


Figure C-2. Simple cascade, no processing of tails.

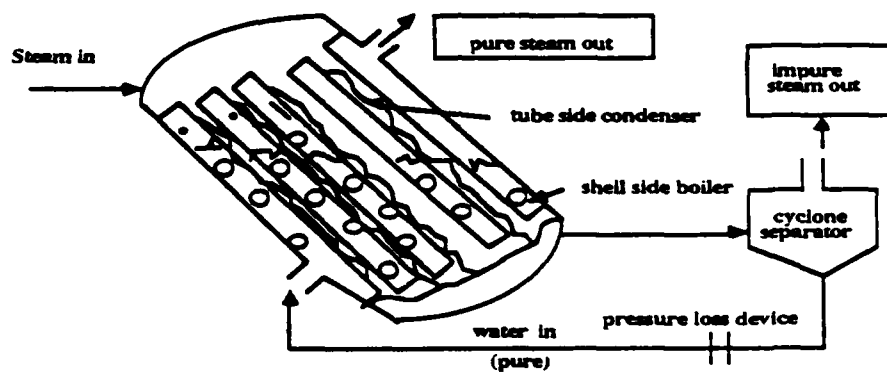


Figure C-3. Schematic of a simple one-stage inverse flash system.

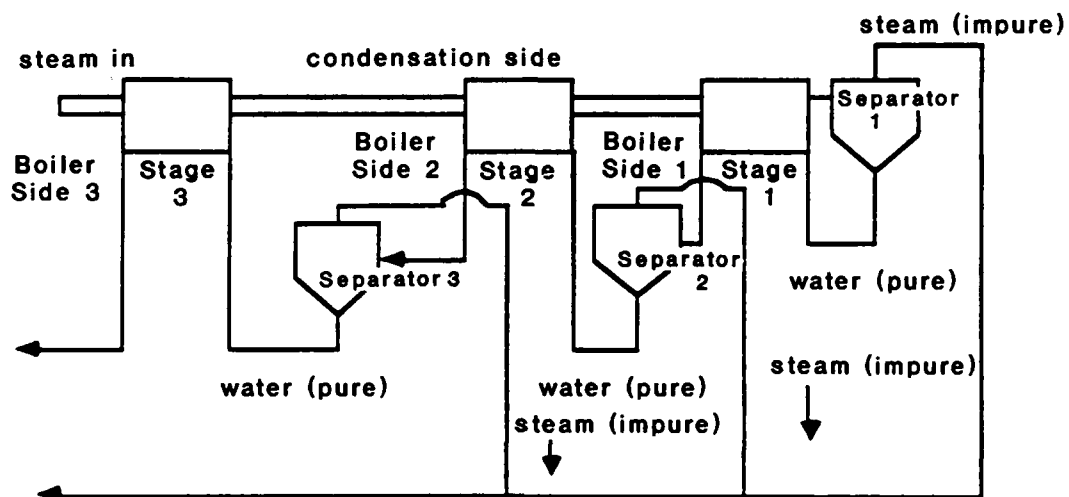


Figure C-4. Schematic showing a three-stage condenser boiler for inverse flash. The separated liquid flowing out of separator 1 is all flashed in three stages by boilers 1, 2, and 3. Each boiler does one-third the flash job.

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